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Polypropylene Fibers In Portland Cement Concrete Pavements

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16. Abstract

This report provides the information obtained from a literature search, site visits, and a laboratory study of polypropylene fibers in portland cement concrete (PCC). The literature search yielded information from numerous laboratory studies of the material properties of polypropylene fiber reinforced concrete (PFRC). The literature showed that, for the low fiber volumes (0.1 percent) recommended by most manufacturers, there was marginal improvement in toughness, fatigue, impact resistance, permeability, shrinkage, and wear resistance. Limited construction has taken place on PFRC suitable for airport construction. Most construction has been of slabs-on-grade and structural slabs. The laboratory study showed that, at 0.1 percent by volume of fibers, the reinforced concrete did not provide appreciable enhancement of material properties over non-reinforced PCC.

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PREFACE

This investigation was conducted by the Pavement Systems Division (PSD), Geotechnical Laboratory (GL), and the Concrete Technology Division (CTD), Structures Laboratory (SL), US Army Engineer Waterways Experiment Station (WES), Vicksburg, Mississippi, for the US Department of Transportation, Federal Aviation Administration (FAA), under Interagency Agreement Number DTFA01-90-Z-02069. This investigation was performed from October 1989 to March 1992. Dr. Aston L. McLaughlin was the Technical Monitor for this project.

This study was conducted under the general supervision of Dr. W. F. Marcuson III and Dr. P F. Hadala, Director and Assistant Director, respectively, GL; Dr. G. M. Hammitt, Chief, PSD, and Mr. H. H. Ulery, Jr., former Chief, PSD; and Mr. T. W. Vollor, Chief, Materials Research and Construction Technology Branch (MRCTB), PSD; Dr. Bryant Mather and Mr. James T. Ballard, Chief and Assistant Chief, respectively, SL; Mr. Kenneth L. Saucier, Chief, CTD; and Dr. Lillian D. Wakeley, Acting Chief, Engineering Sciences Branch (ESB). WES Engineers who were actively engaged in the planning, research, and reporting phases of this study were Messrs. James E. Shoenberger, MRCTB, PSD, GL; and Joe Tom, ESB, CTD, SL.

At the time of publication of this report, Director of WES was Dr. Robert W. Whalin. Commander and Deputy Director was COL Leonard G. Hassell, EN.

METRIC CONVERSION FACTORS

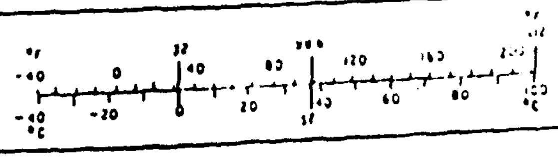
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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INTRODUCTION

BACKGROUND

The addition of various types of fibers to mechanically improve or modify the performance of portland cement concrete (PCC) results in what is called fiber reinforced concrete (FRC). The discrete reinforcing fibers are randomly dispersed within the PCC matrix. The performance improvements attributed to fiber reinforced concrete have been increased flexural, tensile, and dynamic strength, ductility, and toughness[1,2]. The types of fibers commonly used include: steel, glass, polymeric, carbon, asbestos, and natural fibers. The polymeric type include: polypropylene, polyethylene, polyester, acrylic, and aramid fibers.

Historically, the use of fibers as reinforcement in building materials dates back thousands of years and includes the use of asbestos fibers to construct clay pots, straw in making bricks, and hair in construction mortars[2,3,4]. The use of fibers as reinforcement in concrete precedes the use of conventionally reinforced concrete[2]. The modern use of fibers for reinforcing concrete dates from the 1950's to the present[5].

Steel fibers have had the widest usage of any fibers in the paving industry due to their ability to provide increased tensile and flexural strength and fatigue loadings[6]. The steel fibers, because of their high modulus or strength values, provide primary reinforcement similar in effect to steel bars in reinforced concrete[7]. The improvement in material properties which enable the steel fibers to provide primary reinforcement was initially used to justify larger slab sizes and thinner pavement sections. Problems encountered in the field after construction with excessive curling and corner cracking led to the use of more conventional slab dimensions and thickness designs that considered the type of base course material on which the slab was constructed[8].

Polypropylene fibers can not provide the primary reinforcement in a concrete pavement because of relatively low modulus and strength values when compared with steel fibers. Polypropylene fibers are used to provide what is termed secondary reinforcement, or the encouragement of a desired material behavior such as decreased plastic and shrinkage cracking and improved toughness[7]. Polypropylene fibers have been widely used in structural applications since the late 1950's and more recently in paving applications. The predominant paving type of application for polypropylene fibers has been in slab on grade and parking lot construction. Several manufacturers have been selling the fibers to improve the concrete's resistance to the formation of plastic shrinkage cracking and as secondary reinforcement as a replacement for welded wire fabric (WWF)[19]. Polypropylene fibers have had limited use in thick airfield pavements or as overlays on existing PCC pavement.

OBJECTIVE

The purpose of this study was to investigate the effect of polypropylene fibers in PCC mixtures on material properties such as compressive strength, flexural strength, bond, toughness, and fatigue strength. The results of this

investigation are used to develop recommended mixture proportions, construction procedures, and quality control methods. The study includes an evaluation of current practice regarding the use of steel fibers in airport pavements as they pertain to the use of polypropylene fibers.

SCOPE

Polypropylene manufacturers and FRC producers were contacted for information. The laboratory study was conducted with a reference PCC mixture based on information provided by several major airports to represent a standard FAA mixture. Visits to locations involving polypropylene fibers were limited by the small number of ongoing paving projects.

APPROACH

The basic approach to this study was as follows:

a. Conduct an investigation of the various types of polypropylene fibers available and those used in pavement applications.

b. Conduct physical properties tests on various types of candidate fibers.

c. Determine a suitable standard airfield mixture.

d. Determine mixture proportions for each type of fiber and length in regard to mixing and placement.

e. Determine the compressive, flexural, and bond strength, and the toughness and workability for each fiber mixture.

f. Obtain information on previous polypropylene fiber reinforced concrete (PFRC) and visit paving sites as available to observe mixing and placement operations.

g. Review previous work conducted by WES concerning FRC.

LITERATURE REVIEW

STEEL FIBER REINFORCED CONCRETE

Steel fibers are added to the concrete matrix to provide increased flexural and tensile strength, toughness, and dynamic strength (impact resistance)[8]. Steel fiber reinforced concrete (SFRC) is generally more difficult to handle than conventional concrete and requires special considerations in planning and workmanship[5].

The two physical properties that are used to define steel fibers are the length to diameter ratio (aspect ratio) and the geometry of the fiber (straight, hooked, enlarged-end, etc.)[5,10]. In the case of square or rectangularly shaped steel fibers, an equivalent diameter is commonly used rather than the actual width to calculate the aspect ratio.

The large surface area of the steel fibers usually requires an increase in the amount of cementitious material to insure adequate paste for proper coating of fibers and aggregate[11]. The volume of steel fibers used in SFRC has varied from 0.38 to 2.0 percent by volume, with 1.2 to 1.5 percent by volume as the normal upper range[12].

Due to workability problems with SFRC, the nominal maximum size of aggregate in the mixture has usually been either 3/8 or 3/4 inch. Fly ash and other pozzolans, along with air entrainment, and water reducing admixtures have been used in SFRC for pavements[11,12]. SFRC mixtures are usually high in cementitious material content when compared with conventional PPC mixtures[11].

Bulk handling techniques for introducing the fibers into the mixture during the batching operation are the largest adaptation required to the mixing plant. Manual procedures have often been used to introduce the fibers to the mixture[11]. The fibers are usually combined with the aggregates on the charging belt leading to the mixer. In some instances, the mixer has been charged with the fibers first followed by the aggregate, the cement, and then the water[11].

Balling or non-uniform distribution of the fibers is a problem that was often encountered with steel fibers. This problem was intensified in early SFRC by the used of high volumes of straight fibers with small diameters and high aspect ratios. This fiber geometry also caused fibers to pullout of the concrete matrix resulting in poorer than expected engineering properties. The introduction of hooked, corrugated, crimped, or paddeled fibers along with the collation of the fibers with a water-soluble glue, to facilitate handling and mixing of the fibers, has increased the resistance to pullout and also reduced the problem of balling[12]. Collated fibers can be added with the aggregates although they are often added directly to the fluid mixture[12].

The max num size and volume of aggregate can also have an effect on fiber distribution[1]. PCC mixtures with higher volumes of fine aggregate and those which limit the maximum size of aggregate to 3/4 inch have been most widely used to produce SFRC.

SFRC mixtures are generally harsher, with lower workability than conventional PCC mixtures. Air-entraining and water-reducing (both normal and high-range) admixtures are recommended for SFRC[5,6]. One study[13] found that the addition of fibers reduced the amount of entrained air in the SFRC. As the amount of steel fibers increases, the slump and air content of the SFRC will decrease. The rate of slump and air content loss was lower for SFRC with lower cement contents. The addition of fibers also reduced the amount of shrinkage strain[13].

The test methods normally used to measure workability are either slump or inverted slump cone[12]. One study[14] comparing the slump test to the V-B consistometer test (British Standard 1881) as a measure of workability of SFRC versus plain concrete made the following conclusions. (1) The slump test does not provide an accurate indication of workability under vibration. (2) SFRC is more cohesive than conventional PCC, especially at high water contents. (3) Similar effects are obtained in conventional PCC with the addition of a high-range water reducer. (4) The fiber content does not affect the relationship between slump and V-B time. (5) V-B time cannot be used on SFRC mixtures with slumps greater than 3.5 inches.

SFRC has been placed with conventional paving equipment including hand placement, bridge-deck machines, form riding and slip-form pavers. Finishing SFRC is similar to conventional PCC although there is normally less bleed water. Burlap drag texturing has caused tearing of the surface; texturing with a broom or wire comb has been successful.

Proper planning and execution of all phases of design, batching, mixing, and placement operations are needed if problems with fiber balling are to be avoided.

STEEL FIBERS IN PAVING APPLICATIONS

Steel fibers have been used in various airport pavements since the early 1970's[5,8,15]. Due to the increased flexural strength and improved fatigue characteristics of SFRC, airport pavements will have typical design thicknesses of 1/2 to 2/3 that of conventional PCC pavements[8,11]. Design and guidance for construction of SFRC pavements is currently provided in the following US Army technical manuals: TM 5-825-3[16], TM 5-822-6[17], TM 5-809-12[18], and TM 5-822-7[19].

A consideration with SFRC is that the SFRC mixtures allow for thinner pavement sections when compared with conventional PCC and load transfer mechanisms such as keyways and dowels may not be constructable in these thin slabs[20]. Load transfer is assumed across joints between adjacent slabs by current design methods for airfields and parking areas.

The FAA does not include SFRC as a standard paving material in AC 150/5230-6C "Airport Pavement Design and Evaluation," although it has sponsored much of the research concerning the use of SFRC in airport pavements. The current FAA procedure is to approve the use of steel fibers on a specific site or job basis. Steel fibers are not being widely used for FAA airfield pavements at this time.

TYPES OF POLYPROPYLENE FIBERS

Polypropylene is a synthetic hydrocarbon polymer material, first introduced in 1957[2,21]. It is one of a group of synthetic, polymeric fibers (including but not limited to nylon, polyester, and polyethylene) adapted from the textile industry which have been added to PCC in an attempt to improve performance. Currently polypropylene is the most widely used of the synthetic fibers for paving applications[22].

Polypropylene is available in two forms, monofilament fibers and film fibers. Monofilament fibers are produced by an extrusion process through the orifices in a spinneret and then cut to the desired length[1,2]. The newer film process is similar except that the polypropylene is extruded through a die that produces a tubular or flat film. This film is then slit into tapes and uniaxially stretched. These tapes are then stretched over carefully designed roller pin systems which generate longitudinal splits and these can be cut or twisted to form various types of fibrillated fibers[1]. The fibrillated fibers have a net-like physical structure. The tensile strength of the fibers is developed by the molecular orientation obtained during the extrusion process. The draw ratio (final length/initial length), a measure of the extension applied to the fiber during fabrication, of polypropylene fibers is generally about eight.

Polypropylene has a melting point of 165 degrees C and can withstand temperatures of over 100 degrees C for short periods of time before softening[1]. It is chemically inert and any chemical that can harm these fibers will probably be much more detrimental to the concrete matrix[1]. The fiber is susceptible to degradation by UV radiation (sunlight) and oxygen; however, in the concrete matrix this problem is eliminated[1].

Monofilament fibers were the first type of polypropylene fiber introduced as an additive in PFRC. Monofilament fibers are available in lengths of 1/2, 3/4, and 1-1/2 inches (Figure 1). The monofilament fibers have also been produced with end buttons or in twisted form to provide for greater mechanical anchorage and better performance. The majority of fiber manufacturers recommend the fibrillated type of fiber for use in paving applications. The exact chemical composition and method of manufacture may vary slightly among producers. The main types or geometry of fibers currently available from most producers are monofilament and fibrillated. The fibrillated fibers are usually manufactured in bundles or collated together and come in lengths of 1/2, 3/4, 1-1/2, or 2 inches (Figure 2). One manufacturer is producing a twisted collated fibrillated fiber and another is producing a blended collated fibrillated fiber consisting of fibrillated fibers blended together in various lengths from 3/4 to 2 inches.

The monofilament fibers are described by length in inches and also either by mil's (1/1000 inch) or by denier's (unit of fineness equal to the fineness of a 9,000-meter fiber that weighs one gram) in diameter[1]. The term denier comes from the textile industry. The term fibrillated (screen) fiber derives from the manufacturing method used. The term collated means that the fibrillated fibers are bundled together, usually with some type of water-soluble glue which will break up or dissolve in the fluid concrete mixture.

Another method of packaging the fibers used by one manufacturer was in twisted collated fibrillated fibers, for a claimed better 3-dimensional distribution throughout the mixture (Figure 3).

POLYPROPYLENE FIBER REINFORCED CONCRETE (PFRC)

Polypropylene fibers are hydrophobic, that is they do not absorb water. Therefore, when placed in a concrete matrix they need only be mixed long enough to insure dispersion in the concrete mixture[1,2]. The mixing time of fibrillated or tape fibers should be kept to a minimum to avoid possible shredding of the fibers[2].

The type of polypropylene fiber recommended by manufacturers for paving applications is the collated fibrillated fiber. The length of fiber recommended is normally tied to the nominal maximum size of aggregate in the mixture. Manufacturers recommend that the length of the fiber be greater than twice the diameter of the aggregate. This would be consistent with past experiences with steel fibers and also with current theories on fiber dispersion and bonding[1,23].

The manufacturers of fibrillated fibers recommend their products for the following purposes in paving: to reduce plastic shrinkage and permeability, to increase impact resistance, abrasion resistance, fatigue, and cohesiveness (for use in slipforming and on steep inclines), and to provide a cost effective replacement for welded wire fabric (WWF). However, they do not recommend specifying fibers for the control of cracking from external stresses, increased structural strength, slab thickness reduction, joint spacing reduction, or replacement of structural steel reinforcement.

Monofilament fibers, according to fiber manufacturers, only provide control of cracking caused by shrinkage and thermal stresses occurring at early ages. These fibers provide no post-crack benefit and are used only for shrinkage cracking and not to provide improvements to other engineering properties.

The amount of polypropylene fibers recommended by most manufacturers for use in paving mixtures and most other mixtures is 0.1 percent by volume of concrete (1.5 to 1.6 pounds per cubic yard). Researchers have experimented with fiber volumes up to 7.0 percent[24]. Fiber volumes greater than 2.0 percent normally involve the use of continuous fibers, which are not usually considered for paving applications due to constructability problems. Fiber volumes up to 0.5 percent can be used without major adjustments to the mixture proportions. As volume levels approach 0.5 percent, air-entraining and water-reducing admixtures are required[9].

The following results are based on laboratory work with discrete fibers from 0.1 up to a maximum volume level of 2.0 percent. The majority of pavement construction has been done with volume levels of 0.1 percent by weight. Above 2.0 percent by volume, the static strength properties, both compressive and flexural strengths, of the PFRC decrease[25]. This decrease is due to a combination of poor workability, increased segregation and bleeding, and the entrapment of large amounts of air[25]. One study[26] found high

variability in fatigue and static flexural strengths and related this to the inconsistencies of fiber distribution in the tension zone due to randomly oriented fibers.

Compressive Strength

In general compressive strength tests on PFRC specimens show no marked improvement due to the polypropylene fibers[1,2,22,27,28,29,30,31,32,35,36]. Some studies have shown slight increases and others have shown a decrease in the compressive strength of the PFRC. Chemical treatment of the fibers to improve the bond between the fibers and the concrete matrix has been used to provide an increase in compressive strength over non-treated fibers by increasing the mechanical bonding[31].

The concrete compressive strength does not normally show a large improvement due to the addition of any type of fiber reinforcement, including steel fibers[28].

Flexural Strength

Tests results of various researchers have shown that at volume levels from 0.1 to 1.5 percent by volume of fibers in the mixture the PFRC will show only a moderate to no increase in flexural strength[2,22,25,26,27,30,32]. This is in contrast to steel fibers reinforcement where the flexural strength increase may be 50 percent or more[11].

Bond

The term bond as used here describes the adhesion obtained between the individual polypropylene fibers and the concrete matrix in which they are embedded. The effectiveness of the fibers as a concrete reinforcement depends on the bond achieved between the fibers and the concrete matrix. There is no direct physical or chemical adhesion between the polypropylene fibers and the cement gel[1]. Fibers that are twisted or fibrillated, or both, achieve increased toughness and fatigue values compared with monofilament fibers, which supports the concept that polypropylene fiber reinforcement is through mechanical action rather than an adhesive bond[1,2]. An increase in fiber length should result in increased bond for each fiber. One author[9], when testing impact loading with 3/4 inch fibrillated fibers, found minimal fiber pullout indicating that there was a sufficient mechanical bond between the fibers and the concrete matrix.

Toughness

Flexural toughness is considered to be the amount of energy a beam will withstand in flexure before a complete failure occurs. The toughness index is defined as the area under the load-deflection curve up to a specified deflection (various indexes), divided by the area under the curve up to the point of the first crack. The toughness of non-fiber reinforced concrete should be 1.0. Figure 16 shows a typical load-deflection curve.

PFRC has a lower first-crack strength than SFRC due to a lower modulus of elasticity of the fiber[24,28]. The modulus of elasticity for steel can be 30 times as much as that of polypropylene (approximately 1,000 ksi)[24]. The amount of reinforcement provided by the fibers is based not only on their modulus values or tensile strengths but also on the bond which occurs between the fibers and the concrete matrix. Low modulus materials, such as polypropylene, will generally have a large Poisson's ratio. This will cause contraction along the axis of the fibers as they are stretched and will lead to high lateral tensile stresses at the fiber-matrix interface and debonding or fiber pullout[1]. Fibrillation of the fibers increases the surface area and also provides for a mechanical interlocking to help prevent debonding[1]. Chemical treatments of the fiber surfaces (for crystalline growth) to increase bonding have shown slight increases in flexural strength and increased resistance to crack propagation[33]. Mechanical treatments such as twisting of the fibers or fibrillated fibers have improved bond between the fibers and the concrete matrix to significantly reduce fiber pullout[9,28].

Studies have shown that PFRC tends to improve the toughness when compared with conventional PCC and that toughness values increase with increasing fiber contents[2,7,9,27,39]. One study[30] found that PFRC containing 2-1/4 in. long collated fibrillated fibers at 1.6 lb/cu yd showed no increase in toughness, but those with 3.2 to 4.8 lb/cu yd showed an increase. A study on the resistance of mortar[34] to wetting and drying in salt water (based on flexural and toughness properties) found that polypropylene fibers at high volume contents (2.0%) showed the least effect of such exposure when compared with steel and glass fiber reinforced concrete.

Fatigue

The fatigue characteristics are a critical design consideration for paving materials. Flexural fatigue and the endurance limit are important design parameters for pavements that are subject to fatigue loading cycles[26,27]. The fatigue strength can be defined as the maximum flexural stress at which the beam can withstand a predetermined number of cycles of nonreversing fatigue loading. The endurance limit can be defined as the ratio of the maximum applied stress to the static ultimate stress (modulus of rupture) below which failure in fatigue will not occur. The existence and use of an endurance limit is questioned by many researchers[35] and agencies. The use of the endurance limit in design by other agencies can be justified by acknowledging that typical fatigue strength at 10 million cycles is about 55 percent of applied stress to static ultimate stress; therefore, an endurance limit below 55 percent (normally 50 percent) is often used[35]. Improvement in the fatigue properties results in a higher endurance limit, which will result in an extension of pavement service life or permit thinner pavements[27]. The number of cycles of loadings which airport pavements are designed to withstand normally extends from 1,000 to 100,000. Road pavements and possibly some high volume airport pavements must withstand up to 2 million load cycles[27,36]. In one study[32] at about 60 percent of the modulus of rupture the PFRC withstood twice as many cycles of loading as conventional PCC. Polypropylene fibers moderately increased the fatigue strength and improved the endurance limit when compared with a non-fiber reinforced concrete[30]. This effect increased with increasing volume of fibers[26,27]. One study[30] through a limited number of

samples found an increase of 18 percent in the flexural fatigue strength. Figure 22 shows a typical stress-fatigue life (S-N) curve.

Workability

Workability is the measure of the ability of a PCC mixture to be mixed, handled, transported, placed, and consolidated[37]. Three methods are available for use with PFRC: slump, inverted slump cone, and Vebe test.

When fibers are added to a PCC mixture, the slump will decrease. At 0.1 percent volume of fibers their is little correlation between the length of the fiber and its effect on the slump[32]. At these fiber levels the addition of water is not recommended or required as the material will have sufficient workability[23,32]. Reductions in slump of up to 50% have been noted without a loss in workability[28]. There is no direct correlation between the slump and workability for PFRC[30]. The slump test can be used as a quality control test to verify consistency between batches.

At higher volume levels of fibers a high-range water-reducing admixture (HRWR) is recommended to provide workability of the concrete mixture[9,26]. At fiber volumes ranging from 0.5 to 1.0 percent by volume the vebe, slump, and inverted slump cone test were not affected by increasing fiber volume[26,27]. Also, at these levels and below, there was no balling of the fibers[27]. Laboratory tests have shown that for 3/4-in. nominal maximum aggregate size PFRC mixtures, 3/4-in. collated fibrillated fibers at 0.5 percent by volume was the maximum amount of fibers that could be added without major adjustments to the mixture design[9]. At fiber levels of 0.5 and above water-reducing admixtures are required for placement[9,27]. At high volume levels, air-entraining admixtures enhance workability as well as provide protection against freeze-thaw cycles (frost action)[9,27].

Impact Resistance

The impact resistance of PFRC is higher than conventional PCC and increases with increasing fiber volumes. This increase is noted even at low volumes of only 0.1 percent[2,9,27,32]. The impact resistance and shatter resistance of PFRC is partly due to the energy absorbed by the fibers after the concrete matrix has cracked[1]. The fibers improve the impact resistance by providing for a uniform distribution of stresses in three dimensions[31]. PFRC has shown to absorb as much energy as SFRC for the same fiber volume[1]. Fibrillated polypropylene fibers when added to conventionally reinforced concrete beams have improved their cracking resistance under impact and also appeared to inhibit the debonding of the reinforcing steel from the concrete matrix[9].

Permeability

PFRC, when the mixture is workable and properly consolidated, reduces the permeability and moisture absorption when compared to similar conventional concrete mixtures[28]. With fiber volumes of 0.1 percent this can result in permeabilities one-third less than conventional mortar mixtures, provided the water-cement ratio remains below 0.5[38]. One study by a manufacturer[39] showed

that the reduction in permeability increased with increasing percentages of fibrillated fiber (0.1 to 0.3 percent levels evaluated) while increasing fiber lengths from 3/4 to 1-1/2 inches slightly increased the permeability.

Plastic Shrinkage

Laboratory studies have shown that plastic shrinkage is reduced with increasing amounts of fibers[22,38]. PFRC normally has a significantly reduced amount of bleed water and it has been theorized, but, with other researchers disagreeing, that the fibers cause a reduction in consolidation, leading to increased water availability during early hydration and resulting in lower plastic shrinkage[40]. The fibers reduce shrinkage potential (microcracking and crack connectivity) and provide crack control through crack prevention[7,28,32]. Polypropylene fibers act like any other fibers by providing a three-dimensional micro reinforcement to distribute the stresses induced by shrinkage to prevent microcracks developing into significant cracks[41]. Polypropylene fibers act to decrease plastic shrinkage provided that the upper limit of the water-cement ratio remains about 0.5[41].

Wear Resistance

The wear resistance of reinforced and non-reinforced PCC can be judged by several different methods[42]. The studies regarding wear resistance have most often been concerned with wear under the action of studded tires. One study[43] showed that the wear resistance of PFRC increased as the volume of fibers increased up to 2 percent. Only a slight increase was noted between the 0.1 percent level PFRC and non-reinforced PCC.

POLYPROPYLENE FIBER IN PAVING APPLICATIONS

The majority of the PFRC placed by paving methods has been for residential and commercial driveways, for parking lots, and in conjunction with structural applications such as slab-on-grade construction. These applications have typically been placed in relatively thin layers of 4 to 6 inches. PFRC overlays have been applied either as bonded or partially bonded. When these overlays have been bonded to the underlying concrete surface a concrete slurry has been used as the bonding agent. The existing concrete has been cleaned and prepared as is normally done for conventional PCC bonded overlays[19,44].

The usage of polypropylene fibers in thick airport pavement applications has been limited. Those that have been constructed have only been in place for a maximum of 6 to 8 years, and evaluation of their long-term performance is not possible. Locations with PFRC pavement include Lambert-St. Louis International, Houston Intercontinental, and Heathrow Airports.

The reduction in permeability that is obtained with PFRC has been an important criterion in selecting PFRC for bridge decks, parking garages, and other applications where the concrete surface is exposed to salts. Combined with conventional steel reinforcement the PFRC helps to protect the steel reinforcement from corrosion. PFRC has been used to encase electrical cables and equipment to protect them from the effects of moisture.

Polypropylene fibers act to absorb energy, and therefore as the volume of fibers increase, the amount of compactive energy required to achieve a desired consolidation will also increase[1]. At the 0.1 percent level this does not appear to cause any problems; however, if higher volumes of fibers are used, additional consolidation of the concrete to assure adequate compaction will be required.

COSTS

Typical cost for a cubic yard of PFRC from a ready-mix plant with 1-1/2 pounds of 3/4-in. collated fibrillated polypropylene (CFP) would be $4 to $6 over conventional PCC. The cost can increase up to approximately $9 per cubic yard with the longest length, twisted fibrillated fiber. The increased cost of PFRC is mostly for the material itself as the operation of adding the fibers does not greatly increase the costs. The exact cost of the fibers for PFRC would depend on the quantity purchased and the geographical location. There are few cost variations between fiber sizes (3/4 in. versus 1-1/2 in.) as they are sold by the pound and processing costs are the same. There are some variations between types of fibers (monofilament versus collated-fibrillated) with monofilaments costing slightly less due to simplified or less expensive manufacturing procedures. Collated-fibrillated fibers that are twisted or have any other special process involved with them will increase costs several dollars over the cost for collated-fibrillated fibers.

With the flexibility of the fibers and a specific gravity of approximately 0.9 and, polypropylene fibers are much easier to handle than steel fibers. The light weight and ease of handling help to reduce the costs involved in adding the fibers to the concrete mixture. As the fibers can be added almost at any phase of the mixing and transportation process, there are normally no adaptations required to the plant.

The economic basis for using PFRC must involve an increase in the durability and also lower maintenance of the pavement through an increase in ductility, toughness, fatigue, and impact resistance over conventional PCC.

LABORATORY TESTING PROGRAM

GENERAL

The laboratory testing program included an examination of the different types and lengths of polypropylene fibers; the development of an optimal PCC control mixture proportion based upon the manufacturers' recommended dosages of fibers; the manufacturing and curing of PFRC test specimens with five different fiber types and lengths; and the testing and evaluation of six PCC mixtures. The mechanical properties testing program conducted on the PFRC examined and compared PCC mixtures both with and without the introduction of polypropylene fiber-reinforcement.

FIBER INVESTIGATION

A search was conducted to determine the different types and overall lengths of fibers being manufactured and distributed in the United States to not only FAA-related projects but generally to any large pavement (new construction or overlays) projects requiring polypropylene fiber-reinforcement. Six different polypropylene fiber companies manufacture and distribute fibers throughout the United States. Most of the fiber companies have very similar types of fibers; monofilament (single strands of fibers, Figure 1) and collated-fibrillated (multi-strand forming a lattice or web (Figure 2); and one firm also manufactures small twisted bundles of fibers (Figure 3). The lengths of fibers ranged from 1/2-in. to 2-1/2-in., the most common being the 3/4-in and 1-1/2-in. fibers. One manufacturer produces a graded series of fibers (various percentages of lengths from 1/2- to 2-1/2-in. in a single bag).

The review of current fiber manufacturers found that all the companies that manufacture or distribute polypropylene fibers have essentially the same quality of fibers, therefore the testing program did not distinguish between brands of fibers only between types and lengths. Small samples of fibers of each general type and length were obtained for further examination. Several long strands of fibers were also obtained from a number of the companies to aid in the evaluation of the individual fibers and of the polypropylene material. Although the WES materials testing laboratory was not equipped to perform a variety of physical property tests on the fibers, the laboratory was able to determine a few of the properties including tensile strength, elongation, and specific gravity of the fibers and verified some of the physical properties of the fiber material as reported by several of the companies.

The monofilament polypropylene fiber-reinforcement is the conventional straight fiber. The monofilament fibers are either designated by the diameters of the individual fiber strands or by their size. The diameter of a normal monofilament fiber strand is approximately 2.6 mils (0.0026 in.). The equivalent size of monofilament fiber would be approximately 15 deniers. The length of fiber for a concrete mixture is generally selected based upon the nominal maximum size of aggregate; smaller aggregate mixtures require shorter fibers and larger aggregate mixtures require longer fibers.

The collated-fibrillated polypropylene fiber-reinforcement is designed to produce a mesh or webbing as the fiber opens up during the mixing sequence. The webbing feature should provide better bonding and higher pullout resistance. With the multiple interconnected strands, collated-fibrillated fibers are not normally designated by diameter or size as are the monofilament fibers. Collated-fibrillated fibers are generally sold according to length only.

One of the newest concepts of polypropylene fiber-reinforcement to be marketed is the twisted bundles of collated-fibrillated fibers. The design objective of the small bundles is to obtain better distribution of fibers within the batch of concrete; conceptually there should not be any balling of fibers in the concrete mixer with the twisted bundles. The bundles open up during mixing and release the individual fibers for better distribution throughout the mixture. Then, as with conventional collated-fibrillated fibers, the fibers open into meshes or webbing for the increased resistance to pullout.

Several samples of fibers were received for physical properties verification. Long uncut strands of the fibers, monofilament, collated-fibrillated, and twisted bundles were provided by several of the companies to assist in the verification. Table 1 shows the different physical and mechanical properties that were determined using the strands of fibers (Figure 4). The cross-sectional area of the strands was determined from examination from a microscopic view of the ends. However, the specific gravity determination could not be made directly from the loose fiber due to the low density of the material, therefore the material had to be re-formed into a solid bulk of material. The loose polypropylene fibers were placed in a heat press and molded into a solid sheet of material, then tested for specific gravity.

The polypropylene fiber material did exhibit properties similar to those provided in the literature from the companies and from the Handbook of Materials Science[45]. Table 1 shows the comparison of property values determined from the samples received with those of the manufacturers and from the Handbook.

CONCRETE AND CONCRETE MATERIALS INVESTIGATION

There are two methods used by the paving industry to place PCC: fixed-form and slip-form methods. Each method requires a particular range of concrete mixture proportions and properties for placement. The fixed-form method uses concrete placed and consolidated within the forms. After the concrete has set, normally the following day, the forms can be removed. The slip-form method uses slip-form paving equipment, whereby the forms slide with the concrete placement, and the concrete must be able to hold itself after consolidation without undue movement. The two methods must have PCC mixture proportions appropriate for their individual purposes, conventional slump of 1- to 2-in. for formed PCC and a lower slump of 0- to 1-1/4-in. for slip-formed PCC. This investigation used the conventional slump requirements for formed PCC in determining the proportioning of the PFRC.

TABLE 1. MATERIALS PROPERTY VALUES

Property	WES Results	Manufacturer	Handbook
Specific Gravity	0.90	0.90-0.91	0.91
Tensile Strength	est. 45000 psi	40000-110000 psi	45000-80000 psi
Tenacity	4.5 g/denier	n/a	4.5-8 g/denier
Elongation	196% (strain)	8%	15-30%
Modulus	0.0063 lb/denier	0.3-0.7 x10^3 ksi	N/A

* There is no simple conversion from denier to enable an accurate determination of cross-sectional area. Denier relates to fineness; units are measured in grams per 9000 meters of length.

The initial PCC mixture proportions used in this investigation were developed from a number of mixture proportions used by various FAA regional offices and airport facilities engineering departments for new and overlay construction. Airports from St. Louis, Missouri; Atlanta, Georgia; Dallas, Texas; and Los Angeles, California, were contacted concerning recent concrete paving and repair projects. The engineering department at Atlanta's Hartsfield International Airport indicated completion of two large paving projects where a slip-form paver was used in the construction, however, the PCC mixture did not contain fibers. Engineers at the Lambert-St. Louis International Airport had recently completed a rehabilitation project on one of its approach aprons; the PCC mixture did use polypropylene fibers. The PFRC and the PCC pavements used the most recent FAA Advisory Circular[46] as a basis for developing their specifications.

Five portland cement concrete mixtures were proportioned with fibers. Mixture 1 contained the single-strand monofilament fibers. The 3/4-in. fiber length was the most common length distributed and selected for this investigation. Mixture 2 and mixture 3 contained the collated-fibrillated fibers. The 1-1/2-in. fiber length was used in mixture 2 and mixture 3 contained the 3/4-in. fiber lengths. Mixture 4 and mixture 5 contained the twisted bundles of collated-fibrillated fibers. The 1-1/2-in. lengths were in mixture 4 and the 3/4-in. fiber lengths were in mixture 5. Mixture 6, the control mixture, contained no fibers. The type and length of the five different polypropylene fibers used in the six PCC mixtures developed for this investigation are shown in Table 2.

Only one basic concrete mixture was proportioned in the investigation to limit the number of variables associated with the polypropylene fibers. The control mixture, mixture 6, as shown in Table 3 was chosen to represent the wide range of mixtures from the different airports and within the limits of the FAA requirements. This mixture is not considered the optimum for all pavement mixtures with fibers or even polypropylene fibers, but is considered an excellent basic mixture proportion for use with fiber. The manufacturers'

recommendations on fiber volumes and the industry standard amounts were 0.1% by volume or approximately 1.5- to 1.6-lb of fibers per cubic yard of PCC.

TABLE 2. POLYPROPYLENE FIBERS IN CONCRETE MIXTURES

Mixture No.	Fiber Type	Fiber Length, in.
1	Monofilament - single strands	0.75
2	Collated-Fibrillated - multiple strands	1.50
3	Collated-Fibrillated - multiple strands	0.75
4	Twisted-Bundles - twisted bundles of collated-fibrillated	1.50
5	Twisted-Bundles - twisted bundles of collated-fibrillated	0.75
6	None	None

TABLE 3. CONCRETE MIXTURES PROPORTIONS

Mixture No.	Cement lb.	Water (lb.)	Water/ Cement Ratio	Fine Agg, Natural (lb.)	Fine Agg, Crushed (lb.)	Coarse Agg, Natural 3/8-in. (lb.)	Coarse Agg, Natural 1-1/2-in. (lb.)	Air-Entraining Admixture (fl oz)	Polypropylene Fibers (lb.)
1	564	232	0.41	788	474	152	1668	6.2	1.6
2	564	232	0.41	788	474	152	1668	6.2	1.5
3	564	227	0.40	792	476	146	1681	6.2	1.5
4	564	232	0.41	788	474	152	1668	6.2	1.6
5	564	227	0.40	792	476	146	1681	6.2	1.6
6	564	212	0.38	762	457	153	1759	8.5	0

The six PCC mixtures shown in Table 3 were proportioned using Type II portland cement (laboratory stock) and a constant 6-bag cement factor (564 lb of cement per cubic yard of concrete). Laboratory test results on the portland cement are presented in Table 4. The water-cement ratio (w/c) was slightly adjusted to maintain a specified slump of 1-3/4 ± 1/2-in. throughout.

The air content was specified at 5.0 ± 0.5 percent. The mixing water was local city water.

TABLE 4. TYPE II PORTLAND CEMENT TEST RESULTS

Test	ASTM C 150 Requirement	Results
Surface Area, m^2/kg	min 280	361
Autoclave Expansion, %	max 0.80	0.07
Initial Time of Setting, min.	min 60	200
Final Time of Setting, min.	max 600	315
Air Content, %	max 12	8
Compressive Strength, 3-day, psi	min 1500	3000
Compressive Strength, 7-day, psi	min 2500	3430
SiO_2, %	min 20.0	21.3
Al_2O_3, %	max 6.0	4.4
Fe_2O_3, %	max 6.0	2.2
CaO, %	na	63.4
MgO, %	max 6.0	3.8
SO_3, %	max 3.0	2.8
Loss on Ignition, %	max 3.0	0.7
Insoluble Residue, %	max 0.75	0.11
Na_2O, %	na	0.06
K_2O, %	na	0.71
Total Alkalies, as Na_2O, %	max 0.60	0.53
TiO_2, %	na	0.13
P_2O_5, %	na	0.04
C_3A, % (Calculated)	max 8	8
C_3S, % (Calculated)	na	55
C_2S, % (Calculated)	na	20
C_4AF, % (Calculated)	na	7

Four different aggregates with gradings and laboratory test results are shown in Table 5. were used in the mixtures to comply with the requirements of ASTM C 33[47], "Standard Specification for Concrete Aggregates." The manufactured limestone fine aggregate was primarily used to compensate for a slight grading deficiency in the natural fine aggregate. The natural fine aggregate did not contain enough material passing the 0.3-mm (No. 50) and 0.15-mm (No. 100) sieves, therefore the finer manufactured material was used to make up the deficiency. The 1-1/2-in. (37.5-mm) nominal maximum size aggregate is conventionally used in airfield pavements. PCC mixtures intended for use in thin bonded overlays would have limitations on the nominal maximum size aggregate based upon the thickness of the overlay. As a general rule, the nominal maximum size aggregate should not exceed 1/3 the overlay thickness[46].

TABLE 5. AGGREGATE TEST RESULTS

Test	Natural Fine Aggregate	Manufactured Fine Aggregate	3/8-in. Coarse Aggregate	1-1/2-in. Coarse Aggregate
Specific Gravity ASTM C127 & C128	2.63	2.69	2.55	2.55
Absorption, % ASTM C127 & C128	0.50	0.90	2.15	2.10
Grading, Cumulative % passing ASTM C136				
1-1/2 in.				100
1 in.				90
3/4 in.			100	57
1/2 in.			99	30
3/8 in.	100	100	84	17
No. 4	94	99	18	2
No. 8	84	85	5	
No. 16	78	50	4	
No. 30	62	29	3	
No. 50	10	15		
No. 100	1	6		

The air-entraining admixture was a neutralized Vinsol resin. There were five different test fibers, three types and two lengths, used in the investigation. The fibers were the last ingredient added to each concrete mixture (Figure 5). A brief pause was allowed for the concrete materials to be fully mixed prior to the addition of the fibers. The fibers were added slowly by hand sprinkling in through the mouth of the mixer as the concrete was being mixed a second time. One manufacturer has developed a water-soluble plastic bag for easier introduction of fibers into the mixer, however, these water-soluble bags were not used during this investigation. The hand sprinkling technique allows for better distribution of fibers throughout the concrete mixture and reduces the possibility of balling. Following an additional one minute of mixing the fiber-reinforced concrete mixture was discharged from the mixer.

TEST METHODS AND PROCEDURES

Each concrete mixture was made with duplicate batches to permit the results to be evaluated statistically. Replication of mixtures strongly increases the probability of the validity of the testing and of the analysis. Tests were conducted on each mixture to assure uniformity and quality of each batch of concrete. The tests performed on the freshly mixed concrete mixtures were:

a. Slump of Hydraulic Cement Concrete, ASTM C 143[49].

b. Time of Flow of Fiber-Reinforced Concrete through Inverted Slump Cone, ASTM C 995[50].

c. Unit Weight of Concrete, ASTM C 138[51].

d. Air Content of Freshly Mixed Concrete by the Pressure Method, ASTM C 231[52].

Immediately following the tests of the freshly mixed concrete, test specimens were prepared, molded, and cured in accordance with ASTM C 192[53], "Making and Curing Concrete Test Specimens in the Laboratory." The concrete specimens were moist cured up to the day of test, removed from the curing environment, surface dried, and prepared for testing.

"Compressive Strength of Cylindrical Concrete Specimens," ASTM C 39[54], was conducted on test specimens from each batch of concrete to determine the unconfined compressive strength. The 6-in. by 12-in. high specimens were removed from the curing chamber, surface-dried, and the ends of each specimen were capped with a sulfur-based compound to provide for smooth and parallel testing surfaces. The caps were allowed to cure for 2-hr before testing. The specimens were then tested in compression until failure with equipment shown in Figure 6.

"Flexural Strength of Concrete using Simple Beam with Third-Point Loading," ASTM C 78[55], was conducted on test specimens from each batch of concrete to determine the modulus of rupture (flexural strength) of the beam. The beams were removed from the curing environment, surface-dried, measured

for positioning in the support frame and load-bearing surfaces where the concrete was ground smooth to obtain full contact. The specimens were 6-in. by 6-in. by 36-in. long. The length allowed for each specimen to be tested twice. One 18-in. half was tested on equipment shown in Figure 6 and then reversed for the other 18-in. half. Therefore, a single beam provided two results.

"Bond Strength of Epoxy-Resin Systems Used with Concrete by Slant Shear (Modified)," ASTM C 882[56], was modified slightly to evaluate the bonding performance of two concrete surfaces rather than an epoxy-resin system. The 6-in. by 12-in. high concrete test specimens were cast in two separate lifts. The control portion of the slant bond specimen was a 3500-psi non-fiber-reinforced concrete. They were cast as full cylindrical specimens then sawed into two slant halves at approximately 7-day age or 3000-psi strength and allowed to moist cure for the remaining 28-day period. The saw-cut surfaces of the precast bond specimens were sand-blasted to roughen the bonding surface as overlaid concrete surfaces are frequently sand-blasted to increase the potential for a bond to develop between the two surfaces. Just prior to the casting of each of the six test mixtures, the slant surfaces were moistened with water to avoid the loss of mixing water through absorption by the older concrete. These specimens were also capped with the sulfur compound to obtain smooth and parallel ends. These specimens were tested in compression as shown in Figure 7.

"Flexural Toughness and First-Crack Strength of Fiber-Reinforced Concrete using Beam with Third-Point Loading," ASTM C 1018[57], was conducted to determine the energy absorption capability or what is commonly referred to as the "toughness" of FRC. The flexural beams were 6-in. by 6-in. by 36-in. long. The 36-in. length allowed for two tests from one beam specimen. Flexural toughness is considered the amount of energy that concrete will sustain in flexure before a failure occurs. Non-fiber-reinforced concrete has little or no energy absorbing capability, therefore the introduction of fibers into a concrete mixture should provide an increase in the energy absorption capabilities as a result of the inclusion of polypropylene fibers in the concrete matrix. Toughness is measured in terms of area under the load-deflection curve.

Fatigue, ACI 544.1R[5], is the high frequency cyclic loading of a concrete element to failure or to some preset limits of cycles at loads less than the ultimate static load of that element. Fatigue strength is the stress causing failure after subjection to a stated number of cycles of loading. These test specimens were 6-in. by 6-in. by 21-in. long beams. The flexural loadings were applied using the third-point loading reaction frame, ASTM C 78[55] (Figure 8). The high frequency cyclic loadings were applied at 10 Hz (10 cycles per second) to a maximum of 1 million cycles. The constant loading was not allowed to return to zero during the test. The minimum load applied was 10% of the ultimate static load. The maximum load applied ranged from 60% to as high as 90% of the ultimate static load.

Each mixture was produced in two duplicate batches. Each batch of concrete was calculated to produce a sufficient volume of concrete for the individual tests and specimens listed.

a. Compressive Strength — four 6-in. by 12-in. high cylindrical specimens,

b. Flexural Strength — two 6-in. by 6-in. by 36-in. beam specimens,

c. Bond Strength — four 6-in. by 12-in. high cylindrical specimens,

d. Flexural Toughness — two 6-in. by 6-in. by 36-in. beam specimens,

e. Fatigue — two 6-in. by 6-in. by 21-in. beam specimens.

Each hardened concrete test was conducted on the six mixtures at both 7-day and 28-day ages for all tests except fatigue which was tested only at the 28-day age. The concrete specimens were cured in a 100-percent humidity room until time of testing.

TEST RESULTS

The results of tests on the freshly-mixed condition of each PFRC mixture and of the PCC control mixture are given in Table 6.

TABLE 6. FRESHLY MIXED CONCRETE TEST RESULTS

Mixture No.	Slump, in. ASTM C5	Inverted Slump, sec ASTM C995	Unit Weight, pcf ASTM C138	Air Content, % ASTM C41
1	1-3/4	n/a	142.2	5.2
2	2	4.6	142.2	5.0
3	1-1/2	4.3	143.6	4.6
4	2	4.4	141.4	5.5
5	2-1/4	4.2	142.2	5.1
6	1-1/2	n/a	145.8	4.4

The results of the freshly mixed concrete tests indicate the quality control requirements of the mixtures were within those limits normally required in the fixed-form method of concrete placement and in the field construction of pavements and overlays with the exception of mixture 5 whose slump exceeded the limit by 1/4-in. However, mixture 5 was accepted for this investigation due to similar freshly mixed concrete properties obtained between mixture 5 and the other five mixtures.

The freshly mixed concrete was then cast into test specimens for the required hardened concrete tests. The 7-day and 28-day test results of the hardened concrete tests are shown in Table 7.

TABLE 7. HARDENED CONCRETE TEST RESULTS

Mixture No.	Compressive Strength (psi)		Flexural Strength (psi)		Bond Strength (psi)		First Crack Strength (psi)	
	7-d	*28-d*	*7-d*	*28-d*	*7-d*	*28-d*	*7-d*	*28-d*
1	3210	4330	580	655	1840	1890	400	615
2	3080	4070	560	610	1730	2050	525	565
3	3240	4110	615	635	1830	2000	490	650
4	3130	4260	575	675	1370	2130	560	550
5	3620	4600	610	720	1700	2160	705	670
6	3540	4330	620	680	1990	2340	565	660

The results of the hardened concrete tests were calculated from one specimen from each of two replicate batches of concrete. The 7-day unconfined compressive strength ranged from 3080-psi to 3620-psi with the 28-day strengths ranging from 4070-psi to 4600-psi as shown in Table 7. Mixture 2, with 1.5-in. collated-fibrillated fibers, possessed both the lowest 7-day and 28-day strengths at 3080-psi and 4070-psi respectively. Mixture 5, with 0.75-in. twisted bundles, possessed both the highest 7-day and 28-day strengths with 3620-psi and 4600-psi respectively. The control mixture, without fibers, developed compressive strengths of 3540-psi and 4330-psi respectively, mid-range of both the 7-day and 28-day compressive strengths.

The 7-day flexural strength determinations ranged from 560-psi to 620-psi. The 28-day flexural strengths ranged from 610-psi to 720-psi over the six mixtures. Mixture 2, with 1.5-in. collated-fibrillated fibers, possessed both the lowest 7-day and 28-day strengths at 560-psi and 610-psi respectively. Mixture 5, with 0.75-in. twisted bundles, possessed the highest 28-day strengths with 4600-psi. The flexural strength of the control mixture, Mixture 6, in the 7-day test were the highest of the six mixtures at 620-psi, but in the 28-day test, the control mixture results, 680-psi, were in the mid range. Figures 9 and 10 provide top and end views of broken beams fabricated from mixtures 2 through 6.

The 7-day bond strength test results ranged from 1370-psi to 1990-psi. The 28-day results ranged from 1890-psi to 2340-psi as shown in Table 7. Mixture 4, with 1.5-in. twisted bundles of fibers, possessed the lowest 7-day at 1370-psi. Mixture 1, with 0.75-in. monofilament fibers, possessed the lowest 28-day strengths with 1890-psi. The non-fiber control mixture in the bond strength test exhibited the highest bond strengths of all six mixtures

with 1990-psi and 2340-psi strengths at both 7-day and 28-day ages respectively.

The first crack flexural strength test results ranged from 400-psi to 700-psi for the 7-day age specimens. The 28-day specimens ranged from 550-psi to 670-psi. Mixture 5, with 0.75-in. twisted bundles of fibers, showed both the highest 7-day and 28-day strengths at 705-psi and 670-psi, respectively. The lowest strengths were shown by Mixture 1, 0.75-in. monofilament fibers, at 400-psi at 7-day and Mixture 4, 1.5-in. twisted bundles, at 550-psi at 28-day. Mixture 6, the non-fiber control mixture, showed strengths of 565-psi and 660-psi for the 7-day and 28-day age respectively. Figures 11 through 15 provide end views of mixtures 2 through 6.

The first crack toughness test, which indicates the capacity of the material to absorb energy up to the initial crack, was performed on the various concrete mixtures as shown with the results in Table 8. The results of the 7-day toughness test ranged from 51.6-in-lb to 136.3-in-lb. The 28-day toughness test ranged from a low value of 51.1-in-lb to a high of 121.9-in-lb. Mixture 1, with 0.75-in. monofilament fibers, possessed the lowest 7-day toughness capacity at 51.6-in-lb and also the highest 28-day toughness at 121.9-in-lb. Mixture 5, with 0.75-in. twisted bundles of fibers, showed the highest 7-day toughness with 136.3-in-lb. Mixture 4, with 1.5-in. twisted bundles, showed the lowest 28-day toughness at 51.1-in-lb. The control mixture showed toughness values of 82.6-in-lb and 86.3-in.-lb respectively for 7-day and 28-day test, approximately mid range.

Table 8 also exhibits the results of the two toughness indices, I_5 and I_{10}, at 7- and 28-days. The toughness indices are ratios relating the toughness value over a specified deflection from the first crack. The I_5 index is obtained by dividing the area under the load-deflection curve up to a deflection of 3.0 times the first-crack deflection by the area under the curve up to the first crack. The I_{10} index is obtained by dividing the area under the load-deflection curve up to a deflection of 5.5 times the first-crack deflection by the area under the curve up to the first crack. Conventional non-reinforced concrete should exhibit little or no toughness following its initial or first crack, therefore the indices for non-reinforced concrete should be 1.0 or very close to 1. The I_5 toughness indices for these mixtures ranged from 1.2 to 2.3 at 7-day and 1.1 to 1.7 at 28-day. The I_{10} toughness indices ranged from 1.3 to 3.4 at 7-day and 1.1 to 2.3 at 28-day. The non-fiber control mixture, Mixture 6, showed the lowest indices throughout the test as was expected. Mixture 1, with 0.75-in. monofilament fibers, showed the highest 7-day indices for both I_5 and I_{10} at 2.3 and 3.4 respectively. Mixture 4, with 1.5-in. twisted bundles of fibers, showed the highest 28-day indices for both the I_5 and I_{10} indices at 1.7 and 2.3 respectively. Figures 16 through 21 illustrate the first crack and toughness indices at 7 and 28 days cure for each concrete mixture. As the figures show, the results reported were based on from 2 to 4 tests for each mixture. The variation in number of test results was due to the breakage of some specimens in handling or demolding that prevented testing the specimens.

The six concrete mixtures were also subjected to fatigue to determine their resistance to repeated high frequency cyclic loadings. The fatigue test

results are shown in Table 9. These results are based on single specimens, duplicate specimens were not made for the fatigue test. Two mixtures, Mixture 2, with 1.5-in. collated-fibrillated fibers, and Mixture 5, with 0.75-in. twisted bundles of fibers, both exceeded the one million cycle limit without failure at the 60% loading. The same two mixtures, 2 and 5, also showed the higher fatigue capacity at all the loadings. Fatigue strength is measured as the ratio of stress load to maximum static stress required to cause failure after a specified number of cycles. Most PCC structures are conventionally loaded from one to ten million cycles[46]. This investigation limited the maximum cycles to one million cycles because of time constraints. Figures 22 through 26 show the S-N diagrams for each of the six PCC mixtures. Fatigue strength is calculated as the stress ratio at one million cycles. Mixtures 2 and 5 showed the two highest fatigue strength ratios at 64 and 62, respectively. Mixture 6, with no fibers, showed the medium value of 59.

TABLE 8. FIRST CRACK STRENGTHS

Mixture No.	First Crack Toughness, in.-lb		Toughness Index, I_5		Toughness Index I_{10}	
	7-d	*28-d*	*7-d*	*28-d*	*7-d*	*28-d*
1	51.6	121.9	2.3	1.4	3.4	1.5
2	97.0	62.6	1.4	1.5	1.9	1.9
3	77.6	71.2	1.4	1.6	1.7	1.9
4	86.6	51.1	1.4	1.7	1.8	2.3
5	136.3	75.4	1.4	1.5	1.6	1.9
6	82.6	86.3	1.2	1.1	1.3	1.1

TABLE 9. FATIGUE TEST RESULTS

Mixture No.	60-% Load, 10^3 Cycles	70-% Load, 10^3 Cycles	80-% Load, 10^3 Cycles	90-% Load, 10^3 Cycles	Fatigue Strength, ratio
1	421.0	80.1	41.0	5.9	54
2	1000.0	362.3	155.0	6.7	64
3	465.5	76.2	4.2	0.9	57
4	252.3	226.6	75.0	6.3	57
5	1000.0	436.2	79.1	21.3	62
6	506.5	119.1	2.6	0.9	59

STATISTICAL ANALYSIS

An analysis of variance (ANOVA), a statistical procedure which partitions the total variance into known sources of variation, was conducted to determine the significance of the hypotheses of the investigation. Appendix A contains the results of the ANOVA of each individual test property for mixture types, fiber types, and fiber lengths. The hypotheses tested were:

a. There are no differences among the properties of concrete mixtures with or without polypropylene fiber reinforcements.

b. There are no differences among the properties of concrete mixtures with monofilament, collated-fibrillated, or twisted types of fibers.

c. There are no differences among the properties of concrete mixtures with either 0.75-in. or 1-1/2-in. lengths of fibers.

The hypotheses were derived from the concrete mixtures listed in Table 2.

The ANOVA procedure was conducted at the 5% degree of significance. Duncan's Multiple Range Test measures the effects of each concrete property shown to have differences. Duncan's Test determines the significant differences among the means of the test results. Concrete properties are the individual test performed on the specimens, i.e. compressive strength at 7- and 28-day age are two separate and distinct properties. Fourteen of the 15 properties were analyzed and computed with the ANOVA procedure. The 28-day fatigue test contained no replicate data, therefore was analyzed with a ranking procedure. The properties are listed below.

(1) 7-day compressive strength
(2) 28-day compressive strength
(3) 7-day flexural strength
(4) 28-day flexural strength
(5) 7-day bond strength
(6) 28-day bond strength
(7) 7-day toughness
(8) 28-day toughness
(9) 7-day first crack strength
(10) 28-day first crack strength
(11) 7-day I_5 toughness index
(12) 28-day I_5 toughness index
(13) 7-day I_{10} toughness index
(14) 28-day I_{10} toughness index
(15) 28-day Fatigue

Each of the three hypotheses were tested with property 1 through 14. The ANOVA procedure could not delineate any significant differences at the 5% degree of confidence in the fiber length hypothesis, that there are no differences between fiber lengths. The 0.75-in. fiber and the 1-1/2-in. fiber showed no significant differences at the 5% degree of confidence in each of the properties tested.

The remaining two hypotheses, that there are no differences in the properties of concrete mixtures with or without polypropylene fibers (mixtures 1 through 6) and that there were no differences in the properties of concrete mixtures with any of the fiber types, Monofilament (MONO), Collated-Fibrillated (CF), Twisted-Bundles (TB), and No-Fiber (NF), where found not to be true for several of the test properties.

Appendix B contains a graphic representation for comparison of the effect on the following material test properties of the various concrete mixtures, fiber types, and fiber lengths.

Compressive Strength

The ANOVA procedure indicated that there were no significant differences among the properties of concrete mixtures either with or without the polypropylene fiber reinforcements and also no differences among the types of fiber reinforcements at the 5% degree of significance.

Flexural Strength

The ANOVA procedure indicated no significant differences among the mixtures nor among the various types of fibers in the mixtures for the 7-day property. However for the 28-day property, mixture 5 exhibited a significantly higher 28-day flexural strength than mixtures 2 or 3, with mean of 721-psi to 632- and 612-psi respectively. Mixtures 1, 4, and 6 were not significantly different from each other nor from the other three mixtures. The TB fibers exhibited a significantly higher 28-day flexural strength than the CF fibers, with mean of 697-psi to 622-psi. The MONO fibers and the NF mixtures exhibited flexural strengths that were not significantly different from each other or the TB or CF at the 5% degree of significance.

Bond Strength

The ANOVA procedure indicated significant differences among the properties of the concrete mixtures with regard to both the 7- and 28-day bond strength property. Mixture 4 exhibited a significantly lower 7-day bond strength than the other five mixtures which were not significantly different from each other. The 1366-psi mean 7-day bond strength of mixture 4 was significantly lower than the mean of the others whose mean ranged from 1702- to 1991-psi. The NF specimens exhibited significantly higher mean 7-day bond strengths than the TB specimens; 1991-psi to 1534-psi respectively. The MONO and the CF fiber specimens were not significantly different from each other nor the other two types. The mean 28-day bond strength of all six mixtures were not significantly different from each other, however there were significant differences among the types of fibers. The NF specimens exhibited significantly higher bond strengths than the MONO specimens, with strengths of 2338-psi to 1890-psi respectively. The TB and CF were not significantly different from each other nor from the other two types of fibers at the 5% degree of significance.

First Crack Toughness

The ANOVA procedure indicated significant differences among the properties of the concrete mixtures with regard to the first crack toughness property. Mixture 5 exhibited a significantly higher 7-day toughness than mixtures 6, 3, and 1, which were not significantly different from each other. The 136 in.-lb mean toughness of mixture 5 was higher than the 83, 78, and 52 in.-lb mean toughness for mixtures 6,3, and 1 respectively. The type of fibers revealed no significant differences among the TB, CF, MONO, and NF fiber specimens for the 7-day toughness property. For the 28-day toughness property, mixture 1 with a mean toughness of 122 in.-lb was significantly higher than mixtures 2 and 4 who were not significantly different from each other with mean toughness of 63 and 51 in.-lb respectively. Mixtures 6, 5, and 3 were not significantly different from each other nor from the other three mixtures. The MONO specimens with a mean 28-day toughness of 122 in.-lb were significantly higher than the CF and the TB fiber specimens, both exhibiting 67 in.-lb toughness. The CF and TB were not significantly different from each other. The NF fiber specimens were not significantly different from the MONO, CF, nor the TB specimens at the 5% degree of significance.

First Crack Strength

The ANOVA procedure indicated significant differences among the properties of the concrete mixtures with regard to the 7-day first crack strength property but no significant differences with regard to the 28-day strength. Mixture 5 exhibited a significantly higher mean 7-day strength with a mean strength of 705 psi than any of the other mixtures. Mixtures 6, 564 psi, mixture 4, 559 psi, mixture 2, 522 psi, and mixture 3, 489 psi, were not significantly different from each other. Mixture 1, 398 psi, exhibited the lowest 7-day first crack strength but was not significantly different from Mixture 3. The TB and NF specimens with 7-day strengths of 632 and 564 psi, respectively, exhibited significantly higher strengths than the MONO specimens with 398 psi strength. The TB and NF specimens were not significantly different from each other nor from the CF which was significantly different from the MONO specimens for the 7-day first crack strength property. All the mixtures and all the fiber types exhibited no significant differences among themselves at the 5% degree of significance.

Toughness Index 5 (I^5)

The ANOVA procedure indicated significant differences among the properties of the concrete mixtures with regard to both the 7-day and 28-day toughness index, I_5, property. Mixture 1 with an I_5 of 2.3 was significantly higher than all the other mixtures which were not significantly different from each other as their I_5 ranged from 1.4 to 1.2. The MONO fiber specimens exhibited an I_5 that was significantly higher than the other fiber types that were not significantly different from each other. For the 28-day toughness index property, mixture 4 with an I_5 of 1.7 exhibited a significantly higher index than mixtures 1 and 6 which were not significantly different from each other with indices of 1.4 and 1.1 respectively. The I_5 of Mixture 4 was not significantly different from the indices of Mixtures 3, 5, and 2 that were not significantly different from the I_5 of Mixture 1. For the fiber types, the

indices of types TB, CF, and MONO were not significantly different from each other, however, the TB and CF indices were significantly higher than the NF fiber I_5 which was not significantly different from the MONO I_5 at the 5% degree of significance.

Toughness Index 10 (I^{10})

The ANOVA procedure indicated significant differences among the properties of the concrete mixtures with regard to both the 7-day and 28-day toughness index I_{10} property. The mean I_{10} of mixture 1 exhibited a significantly higher 7-day toughness index than all the other mixtures. Its I_{10} was 3.4 to the others 1.9 to 1.3 range. All the other mixtures' indices were not significantly different from each other. The toughness index of the MONO fiber was significantly higher than all the other fiber types whose indices were not significantly different from each other. For the 28-day toughness index I_{10} property, mixture 4, with an I_{10} of 2.3, was significantly higher than mixtures 1 and 6, which were not significantly different from each other with indices of 1.5 and 1.1 respectively. Mixture 4 was not significantly different from mixtures 5, 3, and 2 whose indices were all 1.9. Mixture 1 although significantly different from mixture 4, was not significantly different from mixtures 5, 3, and 2. For the fiber type hypothesis, the 28-day I_{10} for TB and CF, 2.0 and 1.9, respectively, were not significantly different from each other; nor were the I_{10} for MONO and NF, 1.5 and 1.1, respectively, significantly different from each other. However, the indices of both the TB and CF were significantly different from the indices of both the MONO and NF at the 5% degree of significance.

The fatigue tests contained individual test results; no replicate specimens were cast. The ANOVA procedure may only be conducted when replicate specimens are available. The fatigue results were ranked using a rank averaging procedure. Using the ranking procedure with one being the highest and six being the lowest; the six PCC mixtures were ranked in each of the four loading percentages based upon the number of cycles each specimen achieved under the loading requirements. Mixture 5 exhibited the highest overall ranking of the six mixtures. However, mixture 2 exhibited highest overall fatigue strength ratio, at 64, based upon one million cycles of loadings as calculated from the S-N diagrams presented earlier in this report. Mixtures 2 and 5 represent two different types and two different lengths of fibers. The NF mixture, mixture 6, was centered among the rankings and among the flexural fatigue strength ratios.

FIELD STUDIES

GENERAL

The information presented in this part of the report is based on information obtained from contacts with manufacturers, users of PFRC, surveys of previous PFRC construction, and from visits to construction sites using PFRC.

EXISTING POLYPROPYLENE FIBER REINFORCED CONCRETE (PFRC) PAVEMENT

Polypropylene fibers have had limited usage on airport pavements. The PFRC placed on the parking aprons and taxiways at Lambert-St. Louis International Airport has been the only large application on airport pavements. In 1985 approximately 18,000 sq yd of PFRC was placed along with a similar amount of conventional concrete on parking aprons. To date, there has been no noted variation in performance between the PFRC and the non-fiber PCC pavement types. Load transfer devices have been placed in the longitudinal joints at slab intersections in both the PFRC and the conventional non-fiber concrete sections. The pavement sections are visually similar, each contain some slabs with small center cracks and some joint spalling. Due to airplane traffic on the apron, detailed observation and exact quantification of distress was not possible (Figure 24).

Surveys of performance[29,58] have shown that at the 0.1 percent by volume level of fibers the PFRC will not perform well in situations where conventional concrete would not be expected to perform well. The problems encountered included: over sized slabs, reflective cracking, curling, and delamination in bonded slabs. Actual performance is difficult to judge due to the lack of control sections at each location and the variations between PFRC locations. Some conclusions that were drawn from one study[29] include: (a) PFRC can help control plastic shrinkage cracks and bleeding, (b) PFRC will not provide significant crack control after the crack has formed, (c) the toughness and impact resistance of PFRC should provide better spall and ravelling resistance, but this has only been demonstrated from this study in joints and not in cracks, (d) the polypropylene fibers will not provide significant load transfer at joints and cracks due to a low modulus value and poor bond, (e) some poor performance may have been caused by the uncontrolled addition of water to correct the slump loss associated with PFRC. A lower than normal slump should be allowed (not lower workability) and water-reducing admixtures may be added. Another study[58] found that slabs where the joint spacing in feet was less than 2 to 3 times the slab thickness in inches performed well with very little cracking or small cracks if they occurred; this is only slightly larger than the dimensions recommended for plain (nonreinforced) PCC pavements. This is the same general rule-of-thumb used for joint spacing with plain PCC slabs.

The largest use of the fibers in a paving application has been for parking lots, driveways, and slabs on grade. Polypropylene fibers have had wide usage in a variety of structural applications, both vertical and horizontal, including shotcreting, curbing, barrier walls, and precast among others.

The majority of PFRC being placed in paving applications has involved pavements with relatively light loads. Some ready-mix producers sell the PFRC as a replacement for WWF. The WWF in most cases is used for two main functions: to control crack width and provide an interlocking of the aggregate for shear transfer[7] across joints and cracks. One problem with WWF is getting it placed in the proper position. While with PFRC the fibers are dispersed throughout the concrete matrix. In most instances the PFRC is sold for its ability to control shrinkage cracks and also for the ability to hold cracks together once they occur[29]. PFRC can provide control of plastic shrinkage cracking when concrete mixtures are placed under less than desirable conditions[29]. Once a crack has formed, a low modulus material, such as polypropylene, will not have the strength required to hold the cracks together. At low fiber levels (approximately 0.1 percent) the polypropylene fibers will have virtually no control over cracks that form[29]. WWF, when placed correctly, will control crack width better than PFRC mixtures with fiber volume ratios of 0.5 or more[29]. One manufacturer recommends not replacing the WWF in areas of soft or questionable base strength in order to hold the pavement sections together if failure occurs, i.e., PFRC is not a replacement for WWF. This type of problem for most pavement sections should not occur as this would be addressed in design.

WWF is sometimes used in instances where longer than normal joint spacing is required. This increase in spacing subsequently increases the probability of intermediate cracking; but the WWF is only intended to hold the cracks together and to prevent faulting[58], not to prevent cracking. While many manufacturers recommend polypropylene fibers as a replacement for WWF, depending on fiber type, none of them recommend an increase in joint spacing for PFRC over conventional PCC[58].

Reinforcement like WWF is not used in paving work, particularly airfields. Most heavy duty airport pavements do not use reinforcement except for special cases such as odd shaped slabs or unusual loading conditions that would cause an increased probability of cracking. The reinforcement is intended not only to hold the pieces or concrete sections together but to enable the slab to continue to carry the load.

MIXING OF POLYPROPYLENE FIBER REINFORCED CONCRETE

The majority of PFRC currently produced for both structural and pavement applications contains approximately 1-1/2 pounds of fibers per cubic yard of PCC. With a specific gravity of 0.9, this results in about 0.1 percent fibers by volume[2]. This volume of fibers has been the most widely used in paving applications. The volume of steel fibers used in SFRC paving applications has varied from 0.8 to 2.0 percent[11]. PFRC can be mixed in a conventional concrete mixer, with no adjustments or changes in procedure other than the addition of the fibers.

The fibers can be added anywhere within the normal mixing cycle, although most are added to the truck mixers prior to filling with the concrete and proper mixing is then accomplished during transit to the job site. Preweighted or presized plastic bags containing the required amount of fibers are available for the volume of PCC mixture placed in the truck mixer. These

bags are generally emptied by the driver of the truck immediately before filling the truck with the PCC. There are also bags of fibers available that dissolve and can be dropped directly into the PCC mixture. In instances where non-agitating transport trucks are used the fibers are normally added with the aggregate.

The problem of balling of fibers, that had initially been a problem with steel fibers, is not a problem with polypropylene fiber volumes of 0.1 percent. Balling of fibers has not been reported on any PFRC mixture placed in a field application.

PLACEMENT OF POLYPROPYLENE FIBER REINFORCED CONCRETE

Placement procedures for PFRC are similar to those of conventional PCC. The addition of the fibers will tend to make the PFRC mixture somewhat less workable at a given water content. Water-reducing admixtures have been used to increase the workability of PFRC without using additional water. The use of air-entraining admixtures will also increase the workability of the PFRC. Air-entraining admixtures are added to provide resistance to freezing and thawing and not for workability. The majority of PFRC placed at the normal fiber contents of 0.1 percent by volume (1-1/2 pounds per cubic yard) are placed without admixtures.

A broom finish is normally applied to most PFRC pavements. The amount of fibers visible on the pavement surface will depend on the mixture proportions, the amount of fiber added, and the amount and type of finishing applied to the surface. FRC finishers believe that less working of the surface in any finishing operation will result in fewer fibers at the surface. Immediately after placement and finishing the PFRC surface will often look "hairy." The fibers which are at the surface will normally disappear within two weeks of placement due to normal fiber degradation when exposed to the atmosphere.

The surface smoothness obtained with PFRC should be similar to that obtained with conventional PCC under the same circumstances.

The joint spacing and depth of saw cuts in paving applications have followed those that are normally used with conventional PCC pavements.

Fabrication of beams and cylinders in the field follow the same methods as used for conventional PCC. The slump test is sometimes used although, depending on the mixture, the slump reading may have to be adjusted or corrected for comparison. The inverted slump cone has also been used in the field for control.

DESIGN CONSIDERATIONS

STEEL FIBERS

The existing airfield pavement design procedure for steel fiber reinforced concrete (SFRC) was developed by Parker[11] and updated by Rollings[8]. The design procedures for both SFRC pavements and overlays are similar to conventional PCC with adjustments for the increased flexural strength and the improved post-cracking load carrying capacity of the SFRC.

The increased flexural strength results in thinner pavement sections when compared to conventional PCC pavement. A problem that can arise with these thinner SFRC pavements is warping. Conventional PCC pavements, if they were constructed this thin, would also experience this type of distress. The warping that has evidenced itself in SFRC pavement cracking, identified by Rollings[8], requires special consideration. This permanent early-age slab curl has evidenced itself in corner breaks, center-slab longitudinal cracking, and cracking over dowel bars. Rollings identified the most probable cause as differential volume change due to early-age shrinkage coupled with larger than normal slab dimensions. He proposed limiting slab dimensions to more closely match those of conventional PCC. SFRC has demonstrated an ability to decrease the amount of spalling along joints and also along any cracks which might occur[11]. Current technical manuals[16,17,18,19] reflect the recommendations of Rollings[8].

The failure criteria used in current SFRC is similar to that of conventional PCC[11]. SFRC does allow for opening of the cracks which is different than that allowed for conventional PCC. Failure occurs for conventional PCC when one-half of the slabs have one or more structural cracks.

POLYPROPYLENE FIBERS

The design of polypropylene fiber-reinforced concrete (PFRC) will consider the increased fatigue endurance and toughness, and impact resistance of PFRC. Polypropylene fibers do not provide an appreciable increase in flexural strength and therefore will not provide for decreased pavement thickness. The PFRC does exhibit an increase in toughness over conventional non-fiber-reinforced concrete, although it is not as great as that of SFRC. This lower toughness value is due to the lower modulus value of the polypropylene fibers when compared to steel fibers. Polypropylene fibers elongate more than steel fibers after the first crack resulting in greater elongation for a given load and therefore less area under the load-deformation curve resulting in a lower toughness value.

Airport pavements receive impact loadings during landings and rapid loadings (impact) during high speed maneuvers such as takeoffs and landings[11]. Full-scale traffic test sections have demonstrated that the dynamic impact loading is not as severe as slow moving loading in terms of pavement performance[15,41]. The increase in impact resistance provided by PFRC over conventional non-fiber-reinforced concrete mixtures[26] should also enhance the performance of the PFRC pavements when subjected to slow moving loads. The

polypropylene fibers should provide for decreased spalling along joints and also along any cracks which might occur.

OVERLAYS

The term overlay is used to describe the placement of a layer of PCC pavement over an existing PCC pavement. The required bond condition of the concrete overlay whether bonded, partially bonded, or unbonded will depend on the same considerations as for conventional concrete overlays. These considerations include among others the condition of the underlying concrete pavement in regards to cracking, joint spalling, and other distresses and the intended use or loading of the pavement.

FRC, due to its somewhat higher costs when compared with conventional non-fibered reinforced concrete mixtures, is usually more economical when placed as bonded overlays. The advantages of using FRC include improved toughness and impact resistance resulting in overall better performance. The performance of bonded overlays is based on several factors including: degree of bonding achieved between layers (resistance to delamination), aggregate type, and type of reinforcement[59]. A study by the Center for Transportation Research[59] found that for bonded overlays on continuously reinforced concrete, SFRC significantly increased the crack spacing in the overlays studied.

SFRC airport pavements have been placed as overlays in relatively thin layers ranging from 4 to 7 inches[11]. The minimum allowable SFRC pavement thickness is 4 inches and even at this thickness the overlays have normally been either partially bonded or unbonded. A study by Rollings[8] illustrated that SFRC would perform poorly under conditions where a conventional non-fiber reinforced concrete overlay would also be expected to perform poorly. The autogenous shrinkage noted by Rollings[8] should be a consideration when using SFRC for thin bonded overlays, as the shrinkage would be detrimental to the bond achieved between the SFRC overlay and the existing pavement along the edges of the slab.

PFRC when placed as an overlay has normally been placed as a thin bonded overlay. Several thin bonded overlays have been placed with PFRC. These overlays have been placed with both bridge deck finishers and also with slipform pavers[3]. The surface preparation and bonding methods used have been the same as that used for conventional concrete bonded overlays. The amount of polypropylene fibers used has been at 0.1 percent by volume or 1.5 pounds per cubic yard of PCC.

The performance of PFRC may be affected by placement in thin sections. The results of tests using ASTM C 1018 have shown that for any type of FRC, the fibers tend to align in the plane of the section placed. There are minimum dimensions for samples regarding aggregate size and fiber length; therefore, test results performed on standard laboratory samples may not relate directly to field performance. Testing for material properties should be conducted on laboratory samples that correspond to the dimensions or thickness of the pavement to be placed[34].

The performance of the thin bonded overlays placed with PFRC is difficult to judge. The PFRC sections have been placed by various methods, under varying conditions, with different materials, and loadings making accurate comparisons in performance difficult. They have performed at least as well as corresponding sections of conventional pavement.

MODIFICATIONS TO CONVENTIONAL PCC CONSTRUCTION PROCEDURES FOR PFRC

The following section details recommended modifications or additions required to the FAA guide specification ITEM P-501 for Portland Cement Concrete (PCC) Pavement for PFRC. Recommended additions or changes to the guide specification are provided along with additional information. A selection must be made where brackets [ ] appear. The appropriate information should be inserted where blank spaces _____ occur.

MATERIALS

501-3.6 PROPORTIONS. (addition to existing section) The slump requirements shall remain the same for PFRC, except that values will be obtained using the inverted slump cone test as determined by ASTM C 995.

The QA/QC practices required for PFRC are similar to those used for conventional PCC paving. The major difference or adjustment required for PFRC pavement construction is in the use of the inverted cone slump test.

The inverted slump cone test is usually used to control workability as it is more repeatable than the normal slump test. One manufacturer has suggested a correction factor of 1.2 to increase the results of a standard slump test for PFRC when placed where an inverted cone device is not available.

501-2.10 POLYPROPYLENE FIBERS. (new section) The fibers shall be 100 percent virgin polypropylene, (fibrillated/ collated fibrillated/ twisted collated fibrillated) fibers. The fibers shall be _____ inches in length.

The relatively small volume of fibers (0.1 percent) recommended by most manufacturers for paving applications require little adjustment when compared to a conventional PCC mixture. The length of the fiber and its geometry will have at least a slight effect on the properties of the PFRC. As fiber length increases the general workability will tend to decrease slightly. Changing the geometry from a monofilament to a fibrillated or twisted fiber will have the same effect.

There are only a few basic sizes and geometries of fibers commercially available. The usual procedure would be to select a type of fiber and strength required and then adjust the mixture for economy and workability, as is normally done for any mixture. Most manufacturers' relate the fiber length not only to the concrete usage but also to the nominal maximum aggregate particle used in the mixture. They recommend that the fiber length be greater than or equal to the nominal maximum aggregate size. Information from laboratory testing and from previously constructed PFRC pavements can be summarized as follows:

a. Admixtures for water reduction and air entrainment have been used for PFRC and the procedures used follow those established for conventional PCC.

b. The use of cementitious materials other than portland cement has not been widespread. However, there are no indications that the use of fly ash or other pozzolanic materials would adversely affect the long term properties of

the PFRC. In the short term a decrease in the initial strength and shrinkage, and an increase in workability would be the expected results.

c. At the industry standard 0.1 percent volume level of fibers, the amount of cementitious material should not vary greatly from that of a similar conventional PCC mixture.

CONSTRUCTION METHODS

501-3.8 MIXING CONCRETE (addition to existing section) The polypropylene fibers shall be added to the mixture after all other materials have been added. The fibers shall be added in the mixing or transit sequence to provide only enough time in the mixture for complete dispersal within the mixture.

The addition of fibers through bulk or automated handling of the fibers has not been developed. Due to the nonabsorptiveness of the fibers they need only to be added in the production process where thorough mixing can occur. The controlling factor used in selecting where the polypropylene fibers will be introduced would be to assure that they were not damaged during the mixing process.

The mixing action and time requirements should be essentially the same as for that of conventional PCC. The main factor to consider would be to prevent any damage by overmixing either at the plant or in the transit-mix truck.

501-3.10 PLACING CONCRETE. (no modifications required of guide specification)

PFRC can be placed with conventional paving equipment. Bridge deck machines, form riding pavers, slip-form pavers, and hand methods have all been used to place PFRC. The addition of fibers will tend to stiffen the mixture somewhat; however, the mixture is often more workable than the slump test indicates[26]. The use of a water-reducing admixture or a HRWR along with an air-entraining admixture can provide the required workability. When transit-mix trucks are used to transport the PFRC, low slump mixtures may be difficult to discharge properly. The use of admixtures will allow lower slump mixtures with this type of transport or delivery system.

A lower apparent slump should aid in slipform paving construction of thicker airport pavements by providing better edge support than conventional concrete at the same water cement ratio.

501-3.13 FINAL STRIKE-OFF, CONSOLIDATION, AND FINISHING (addition to existing section). Overfinishing of PFRC will be revealed by a large amount of fibers floated to the surface. Finishing shall cease or practices modified if excessive floating of fibers to the pavement surface occurs.

The surface of a PFRC pavement can be finished by conventional techniques. Overfinishing of the surface will result in the same problems that would be encountered with conventional concrete such as: crazing, scaling, and other surface problems. Overfinishing also results in an abundance of fibers being brought to the surface. A specific gravity less than one may also add to the

fibers coming to the surface. Skillful floating by workmen during finishing can avoid over exposing or bringing fibers to the surface[1]. With proper placement, consolidation, and finishing techniques it is possible to maintain a uniform distribution of the fibers in the concrete. PFRC pavement surfaces have been both broom and wire comb finished, with a broom finish the most widely used. Compared with conventional PCC, the presence of the fibers in the concrete does not appear to adversely effect the resulting surface texture.

The sawing of contraction joints and later joint preparation should be similar to conventional PCC. The spacing of the joints should be the same as that of conventional PCC because of similar initial strength properties and therefore similar curling stresses in the PFRC and conventional PCC.

CONCLUSIONS

Polypropylene fiber-reinforced concrete mixtures with a fiber content of 0.1 percent are being used in some commercial pavement applications and have been used on several airport pavements. Unlike steel fibers the polypropylene fibers will not provide for a thinner pavement when compared with conventional PCC for a given load carrying capacity.

The laboratory study was based on a generalized airport PCC mixture, with 1-1/2-in. nominal maximum size aggregate and Type II portland cement. The water-cement ratio ranged from 0.38 to 0.41 for the several different types and lengths of polypropylene fibers investigated in this study for use in PCC. This investigation did not investigate the maximum or optimum amounts of polypropylene fiber reinforcements to a PCC matrix; the recommended dosage of 0.1 percent by volume was used.

The following conclusions on PFRC material properties are deemed warranted based upon the laboratory testing program, literature search, and field information collected.

1. The overall performance of the PFRC was not enhanced by either variations in the type or length of the polypropylene fiber, nor by any combination of the two properties.

2. The compressive and flexural strengths of PFRC was not enhanced by the addition of polypropylene fibers.

3. The bond between a non-fiber reinforced concrete base and PFRC mixtures was impeded by the addition of polypropylene fibers. This would make bonded overlays at least somewhat more difficult to construct.

4. The toughness after development of the first crack, toughness indices, was enhanced by the addition of the polypropylene fibers.

5. The fatigue strength of the PFRC mixtures and of the non-fiber reinforced PCC mixture indicated the PFRC mixtures were within the conventional limits of PCC fatigue. No enhancement of fatigue strength was observed from the addition of polypropylene fibers to a PCC mixture.

6. The workability of the PFRC was not greatly affected by the addition of polypropylene fibers at the 0.1 percent level. The literature shows that good workability remains at these fiber levels. Workability decreases with increases in fiber levels. At levels of 0.5 percent and above a water reducing agent or a change in the PCC mixture proportions will be required.

The following conclusions on PFRC material properties are deemed warranted based upon the literature search and field information collected:

1. PFRC, according to the literature, does provide improved impact resistance with increasing volumes of fibers.

2. PFRC mixtures, according to the literature, does provide reductions in permeability provided that the water-cement ratio remains below 0.5. Increased percentages of fibers further decreased the permeability provided the mixture remained workable.

3. The literature study indicates a reduction in plastic shrinkage with increasing amounts of fibers. The polypropylene fibers decrease plastic shrinkage provided the water-cement ratio remains below 0.5.

4. Wear resistance of PFRC has not been widely studied, but one study found an increase in the wear resistance with increasing fiber contents.

At commonly used levels of fiber volume (0.1%) there will be no requirement to change the construction procedures and techniques or jointing procedures currently used for conventional PCC.

RECOMMENDATIONS

The results of this study did not reveal any definite advantages to the use of PFRC for airport pavements. Elimination of WWF with PFRC is not an advantage as WWF is not used for airport pavements. The possible advantages noted in this study for PFRC, such as: decreased spalling, reduced permeability, and increased abrasion resistance can be effectively attained through proper mixture proportioning and construction procedures with non-reinforced PCC.

Figure 1. 3/4-in. monofilament fibers

Figure 2. 3/4 in. collated fibrillated fibers

Figure 3. 3/4-in. twisted collated fibrillated fibers

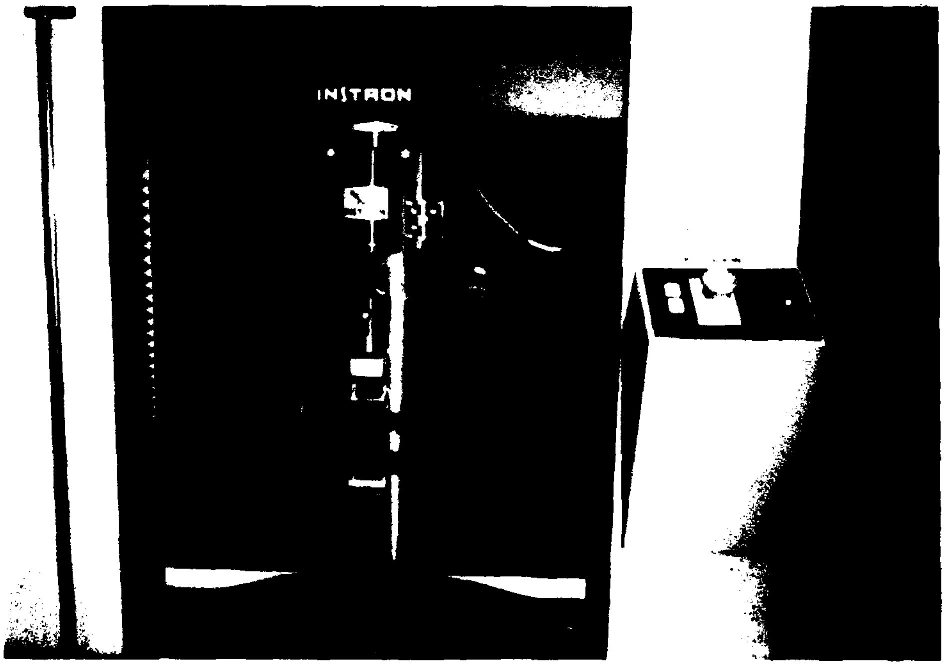


Figure 4. Tensile test machine for fiber strands

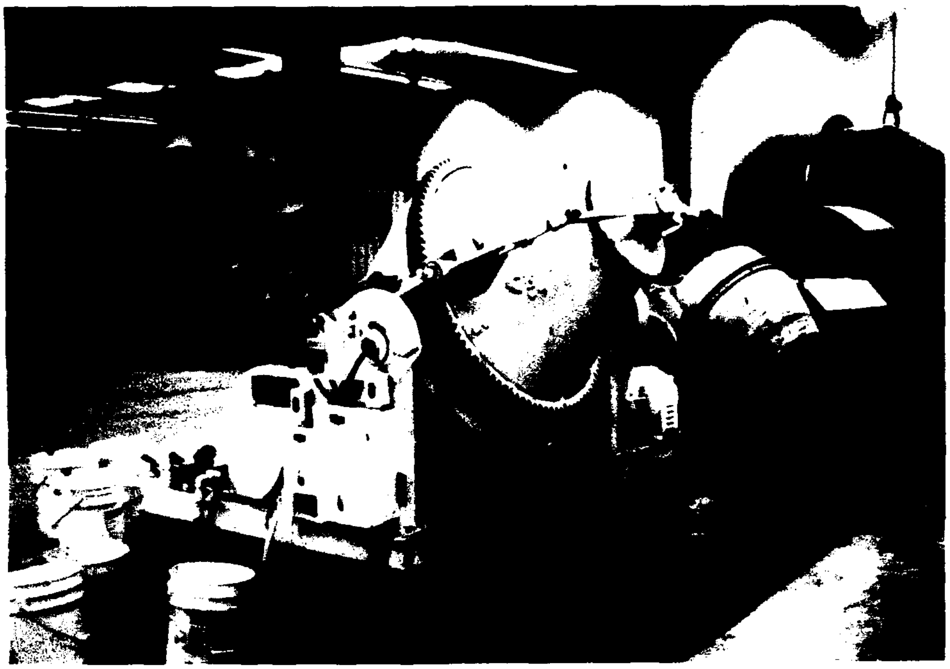


Figure 5. Concrete mixer

Figure 6. Universal testing machine

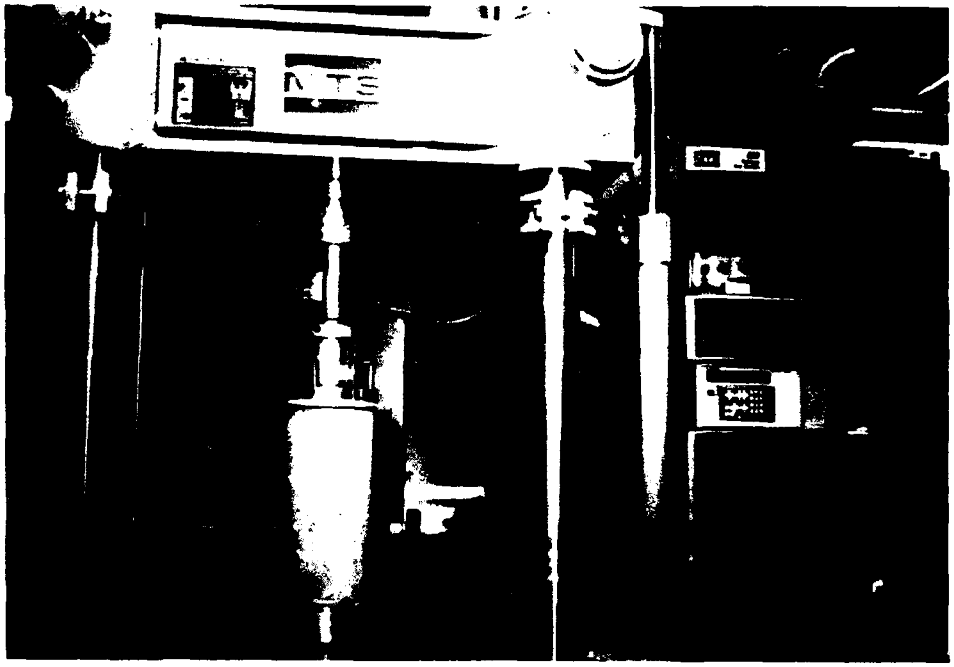


Figure 7. Compression testing machine

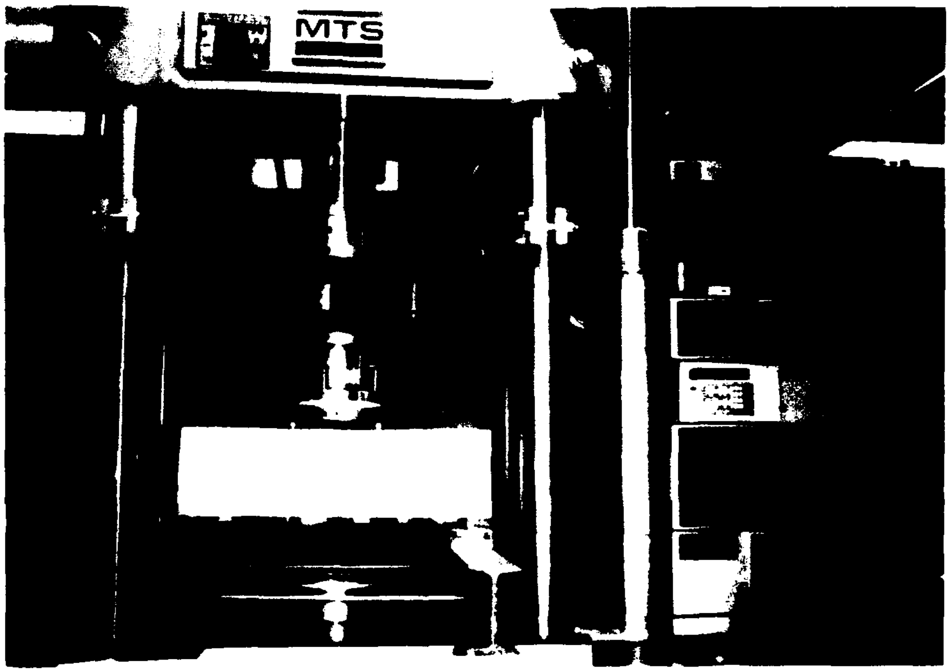


Figure 8. Flexural testing machine

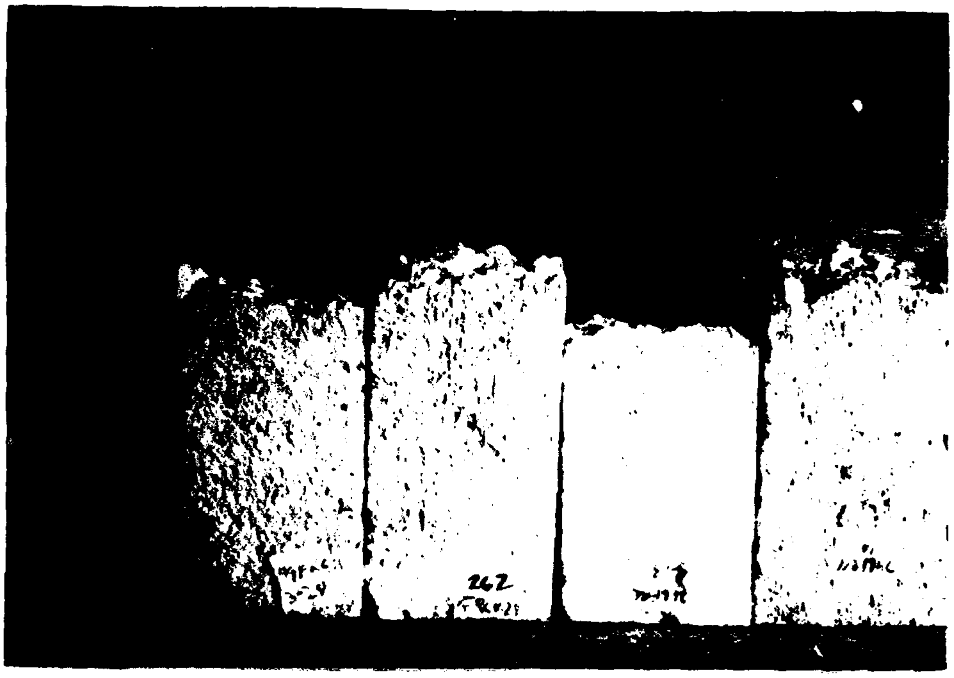


Figure 9. Top view of mixtures 2 through 6

Figure 10. End view of mixtures 2 through 6

Figure 11. Mixture 2, 1-1/2-in. collated fibrillated fiber reinforced concrete

Figure 12. Mixture 3, 3/4-in. collated fibrillated fiber reinforced concrete

Figure 13. Mixture 4, 1-1/2-in. twisted collated fibrillated fiber reinforced concrete

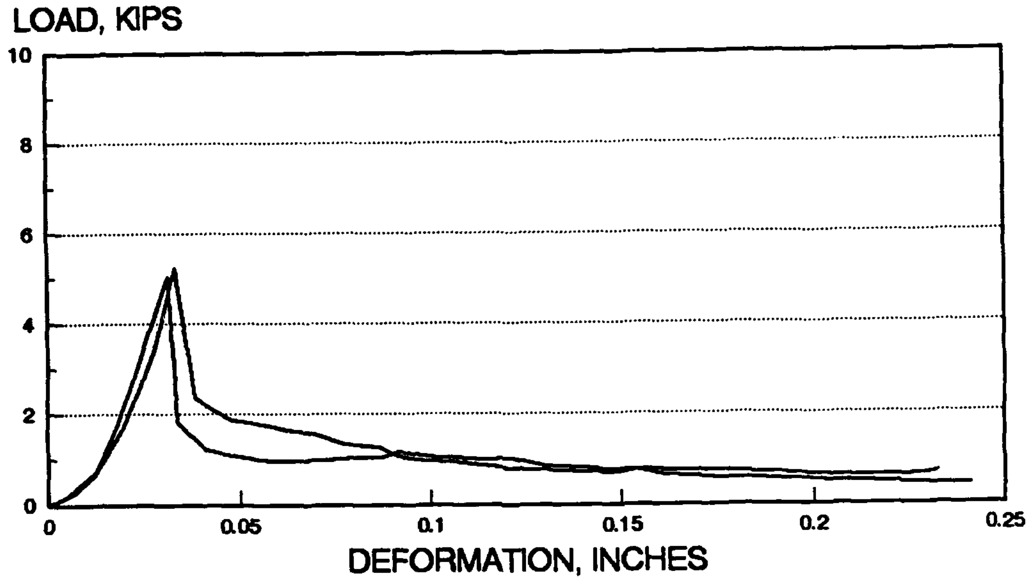
Figure 14. Mixture 5, 3/4-in. twisted collated fibrillated fiber reinforced concrete

Figure 15. Mixture 6, control mixture, no fibers

7 DAY FLEXURAL TOUGHNESS

MIXTURE 1

3/4 IN. MONOFILAMENT FIBERS



28 DAY FLEXURAL TOUGHNESS

MIXTURE 1

3/4 IN. MONOFILAMENT FIBERS

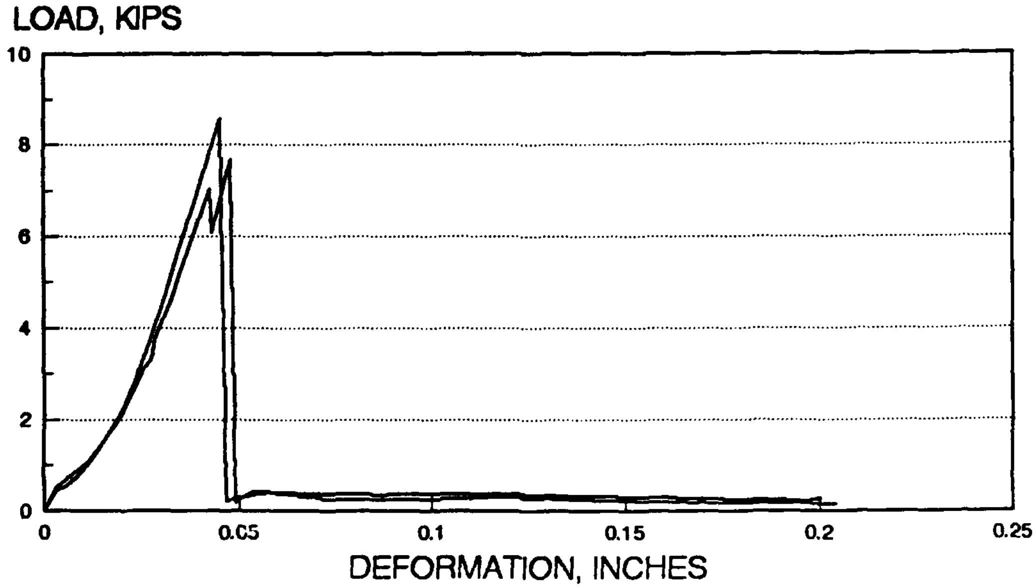
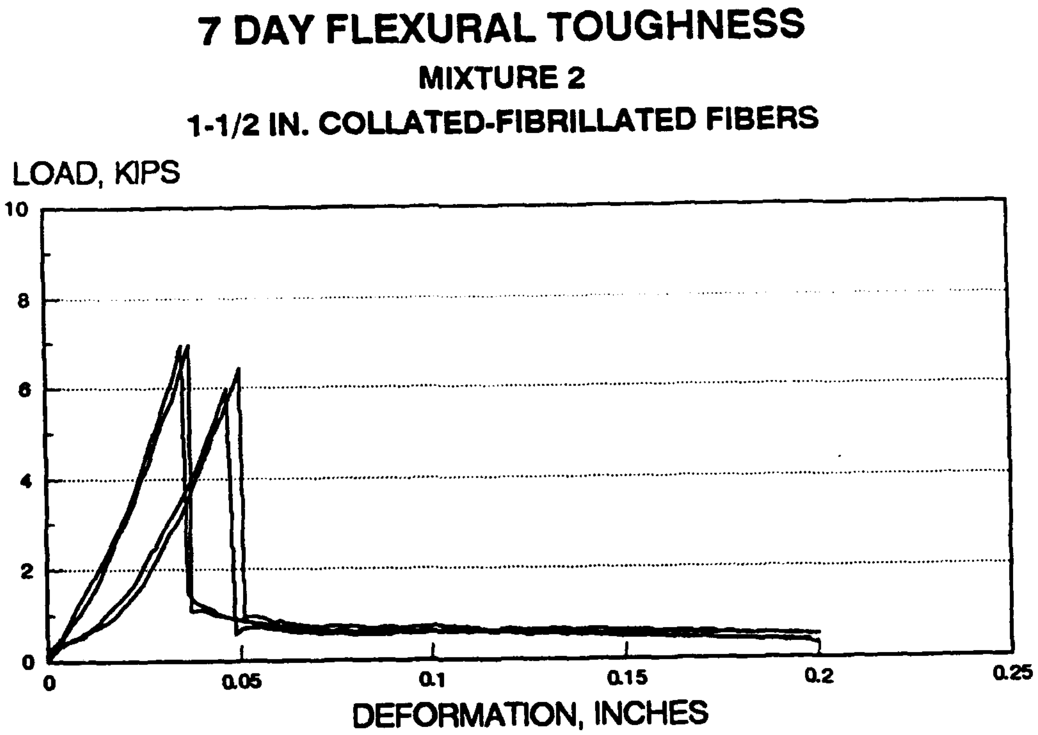


Figure 16. Toughness load-deflection curves for mixture 1



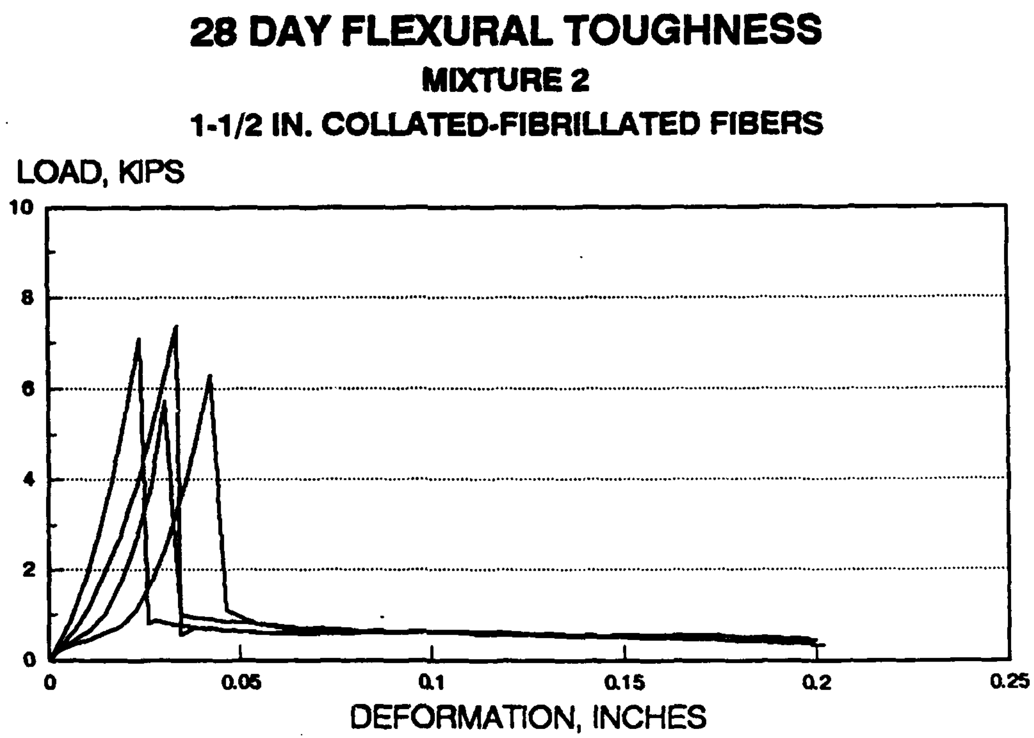
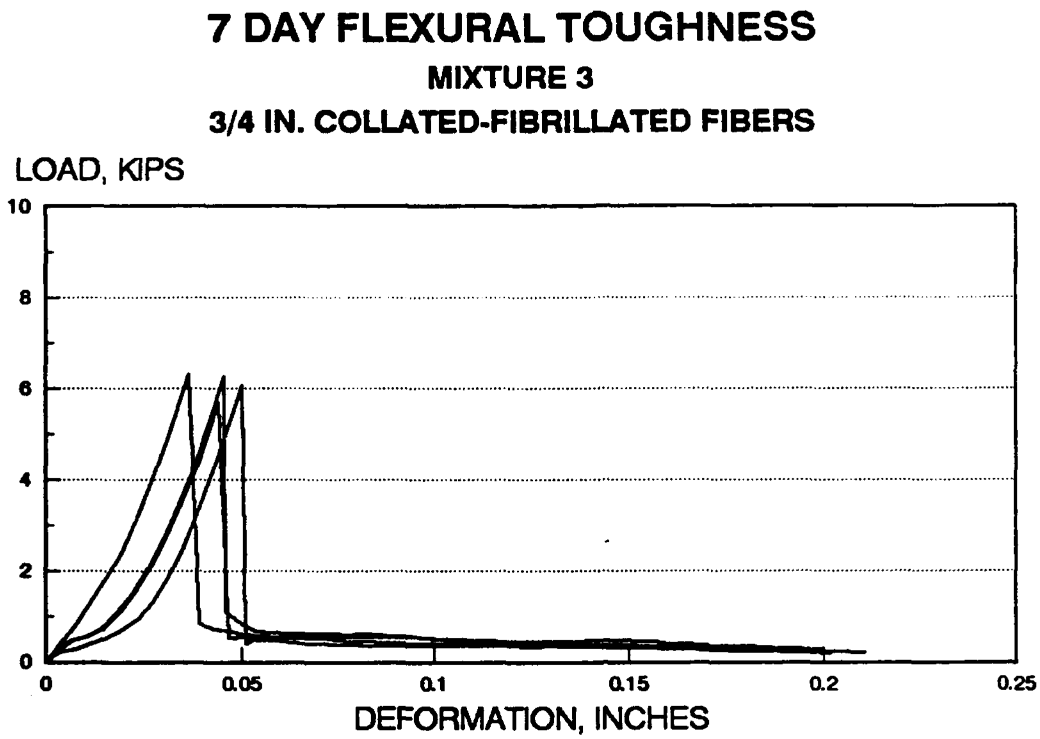


Figure 17. Toughness load-deflection curves for mixture 2



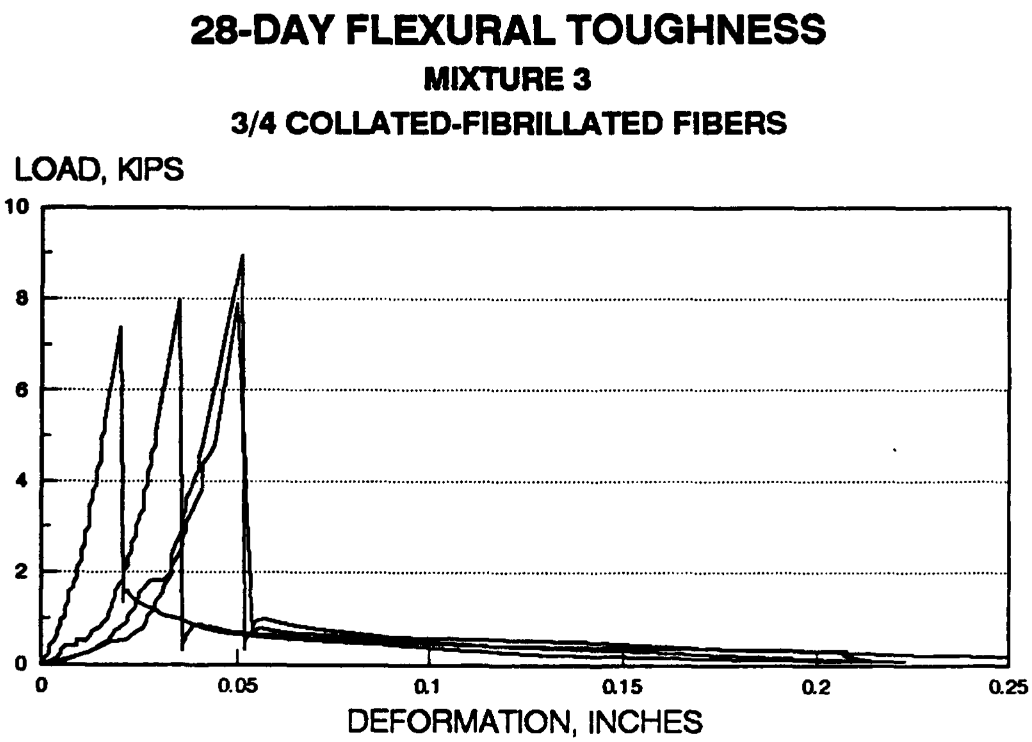
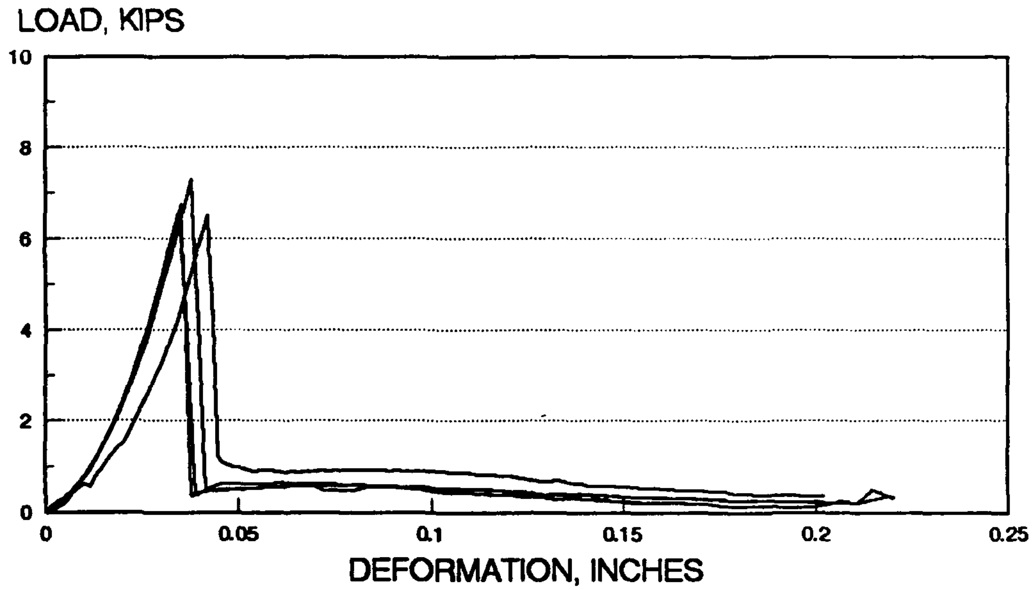


Figure 18. Toughness load-deflection curves for mixture 3

7 DAY FLEXURAL TOUGHNESS

MIXTURE 4

1-1/2 IN. TWISTED FIBERS



28-DAY FLEXURAL TOUGHNESS

MIXTURE 4

1-1/2 TWISTED FIBERS

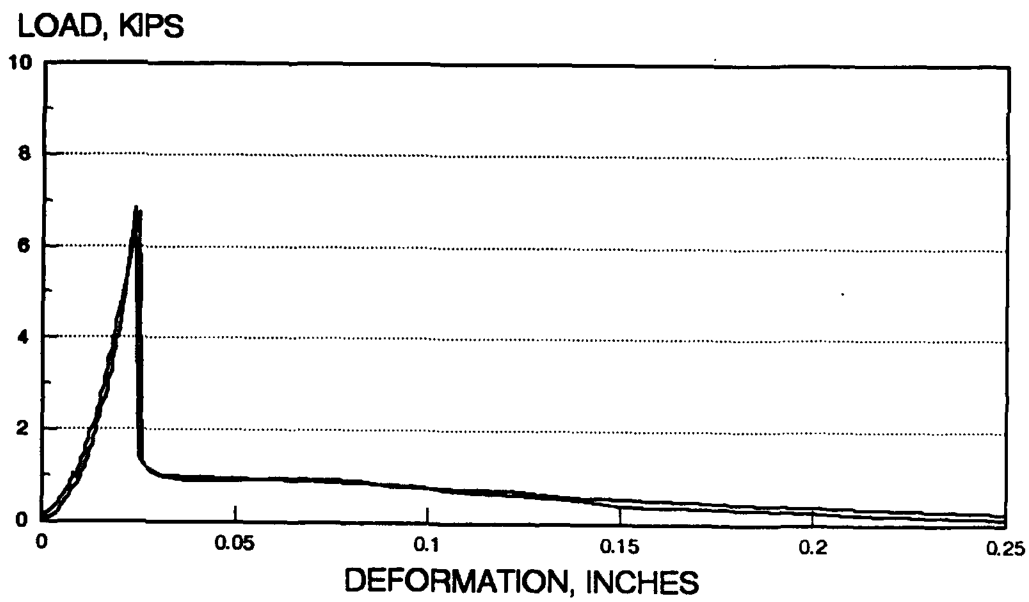
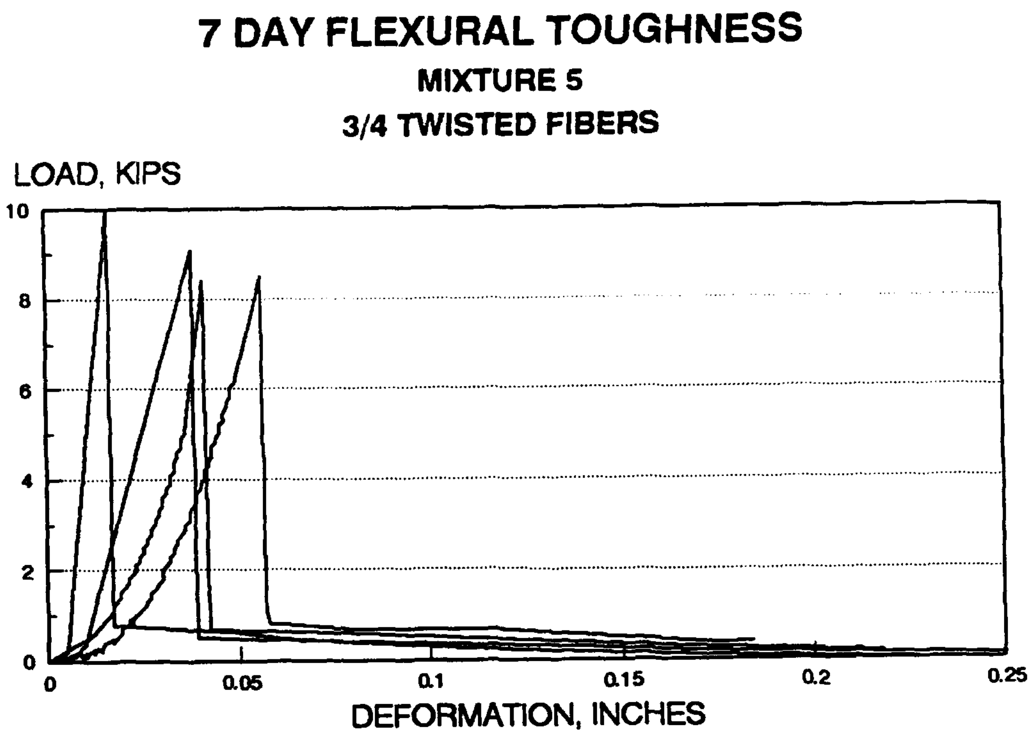


Figure 19. Toughness load-deflection curves for mixture 4



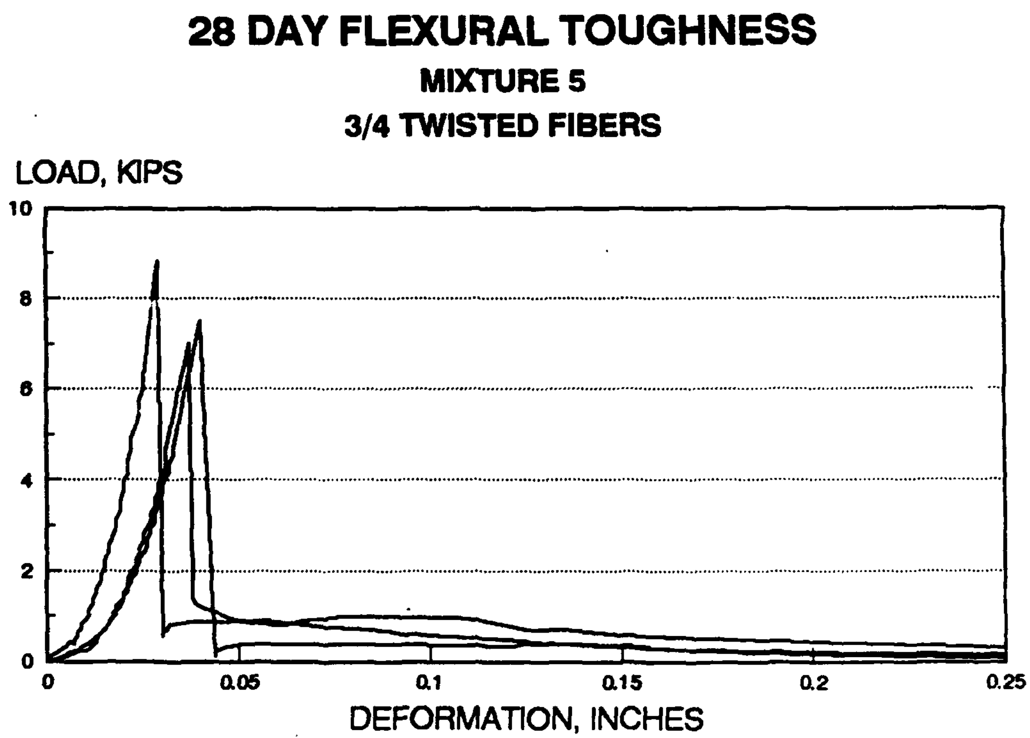
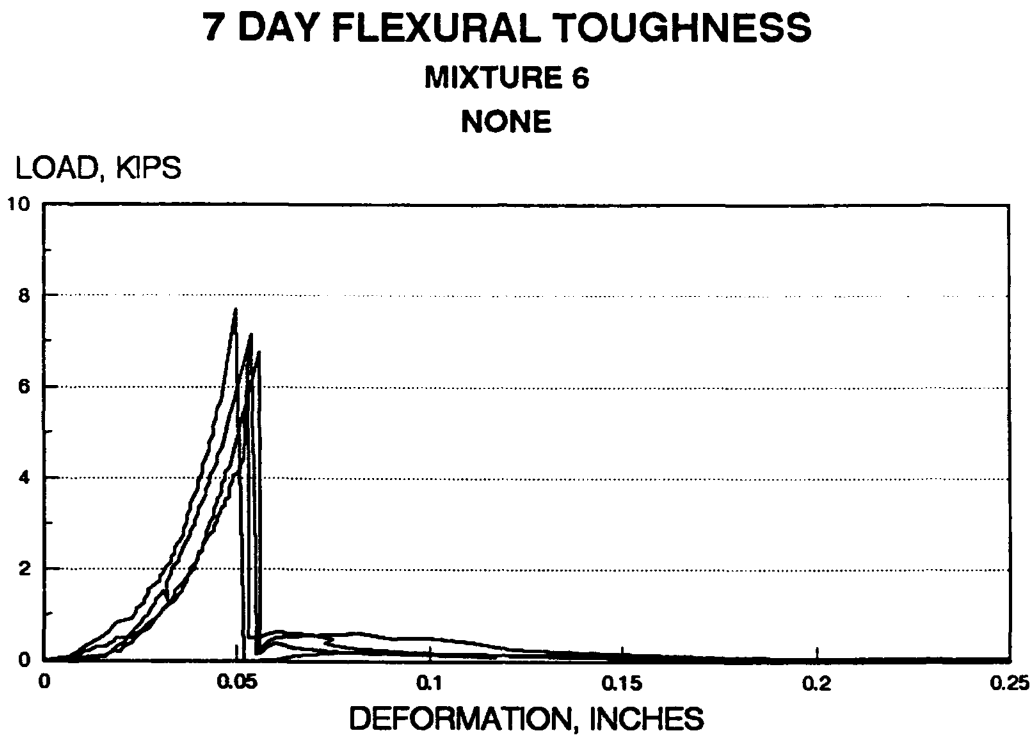


Figure 20. Toughness load-deflection curves for mixture 5



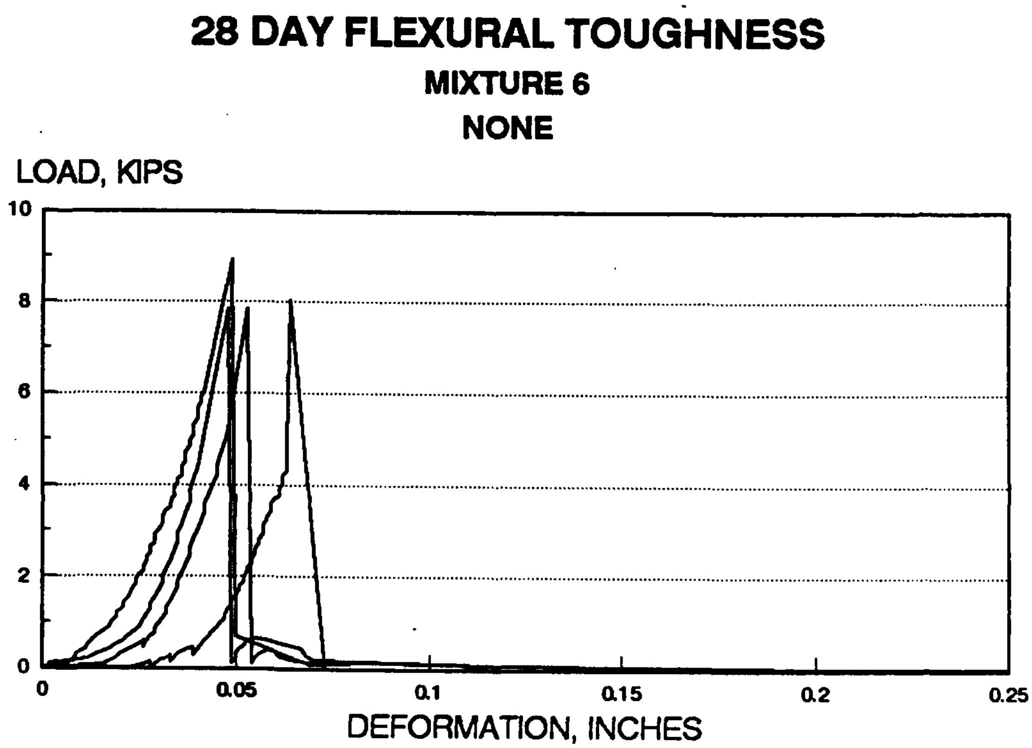


Figure 21. Toughness load-deflection curves for mixture 6

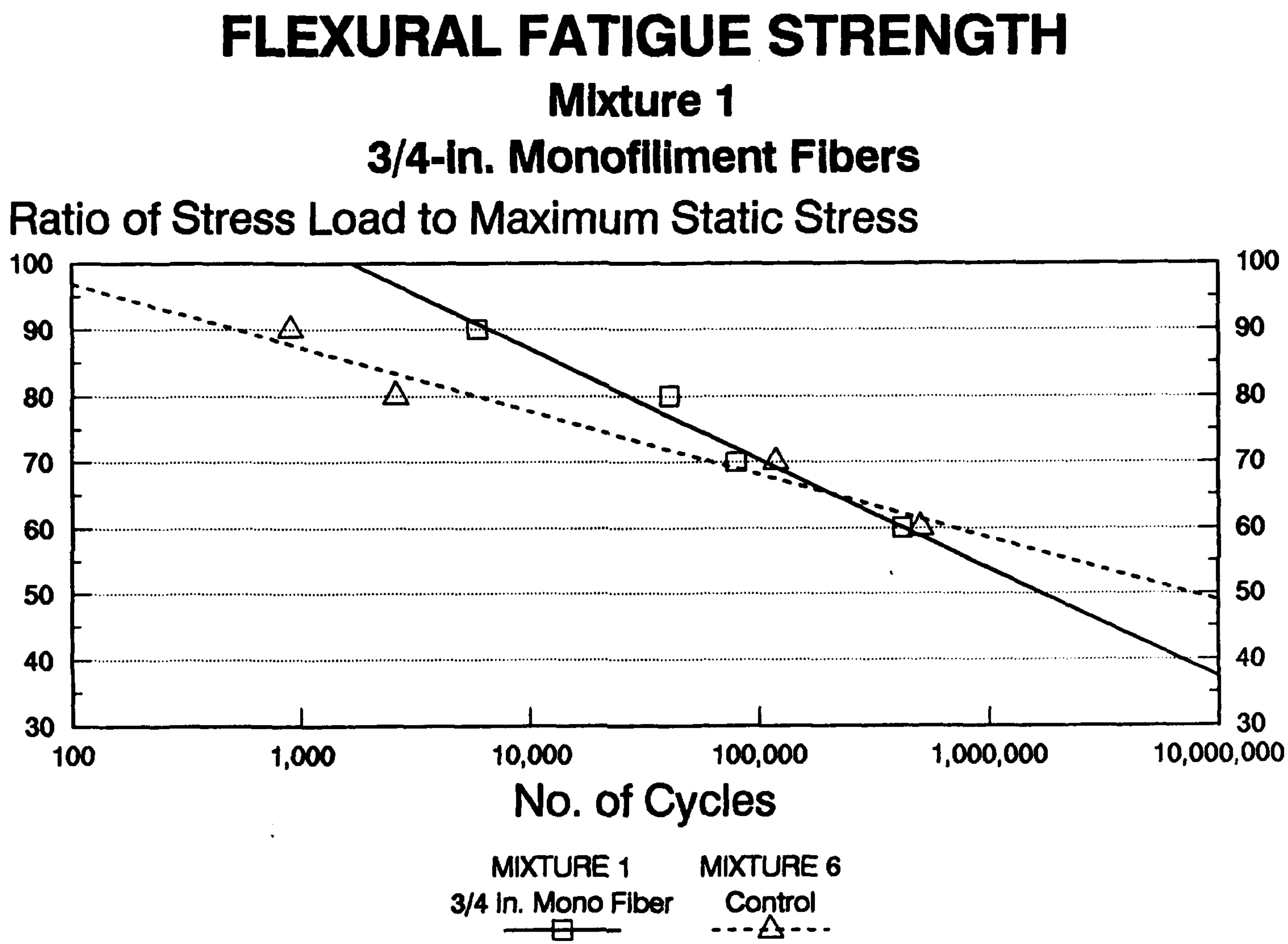


Figure 22. Fatigue curve for mixture 1

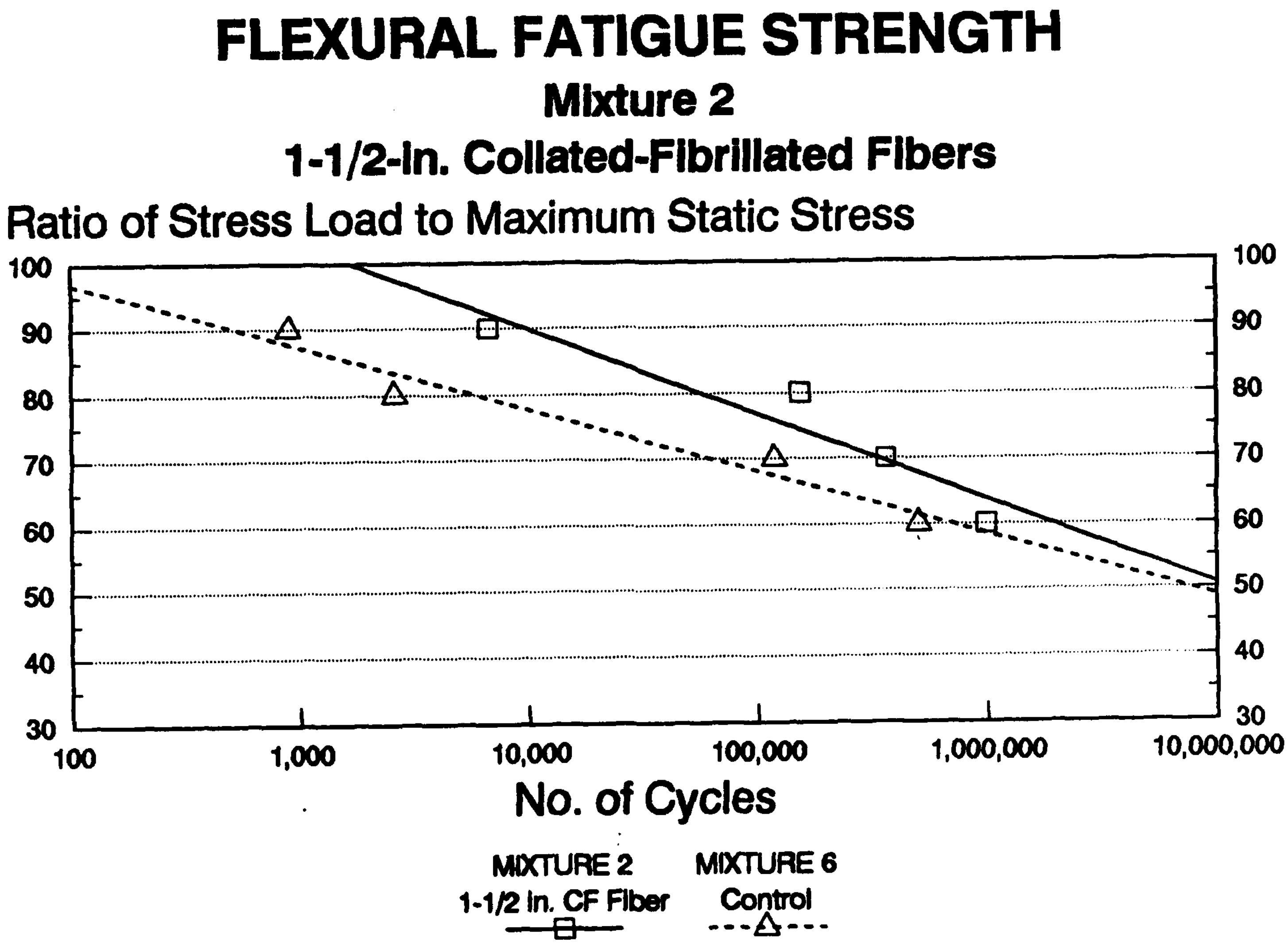


Figure 23. Fatigue curve for mixture 2

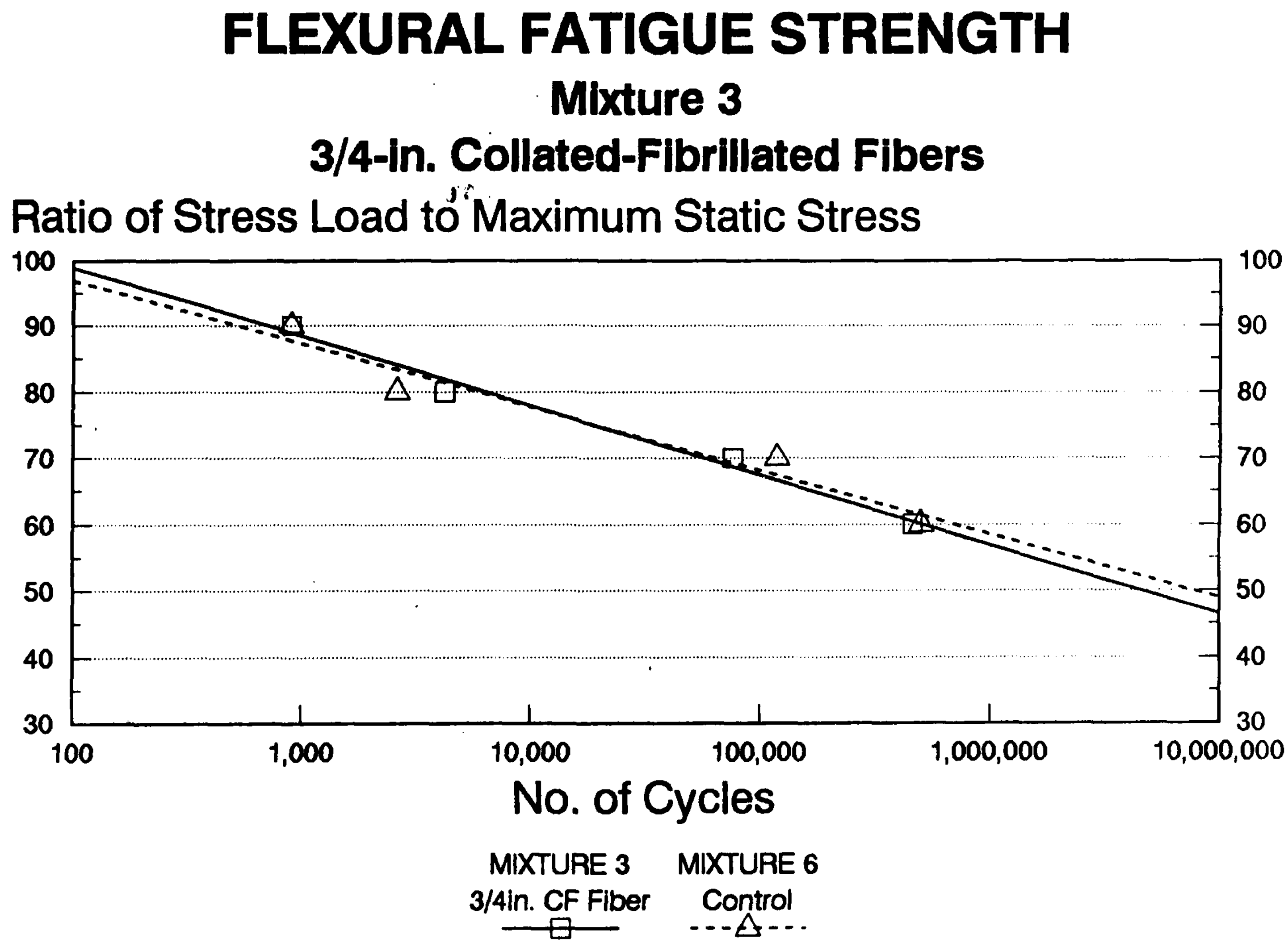


Figure 24. Fatigue curve for mixture 3

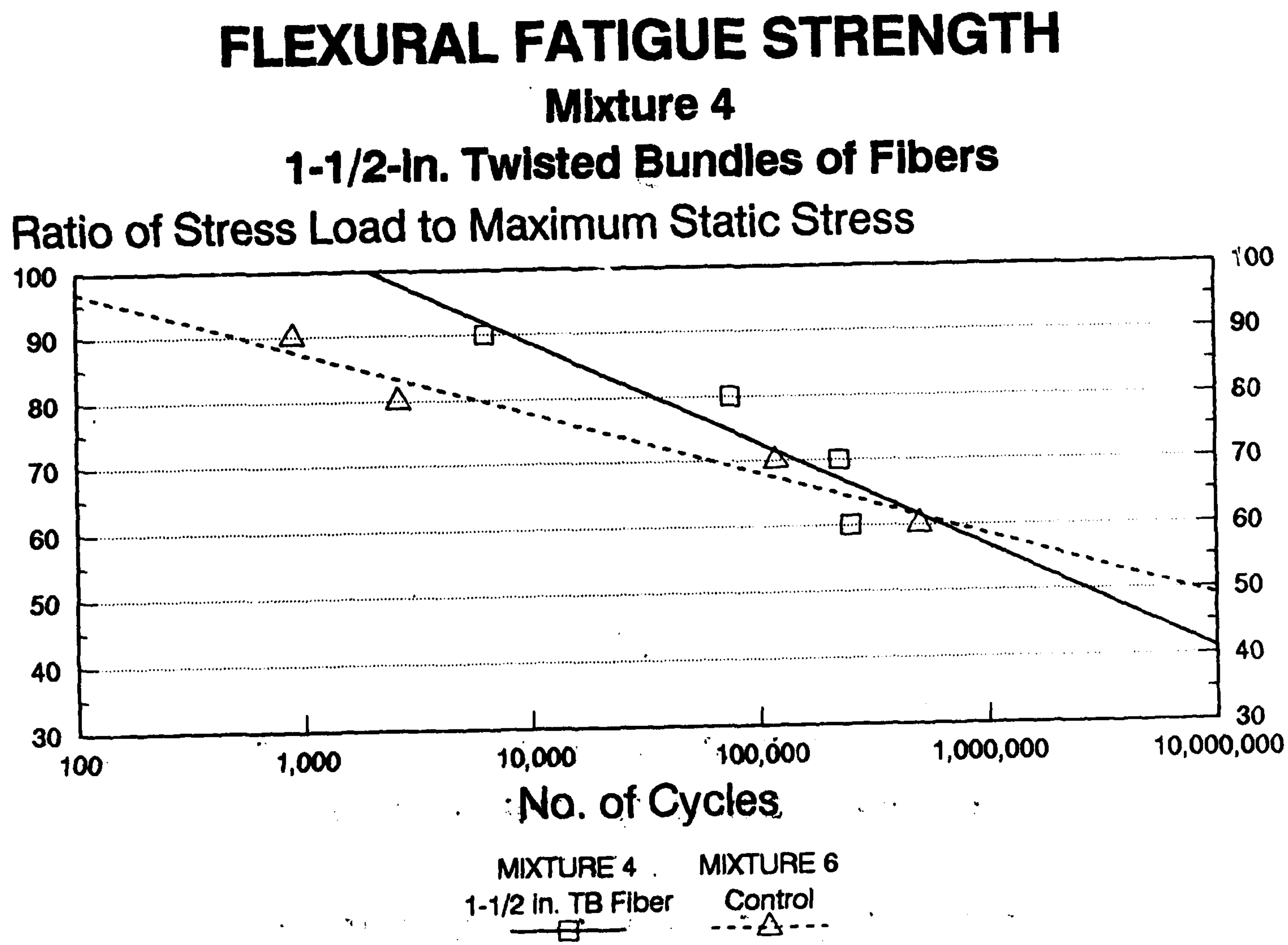


Figure 25. Fatigue curve for mixture 4

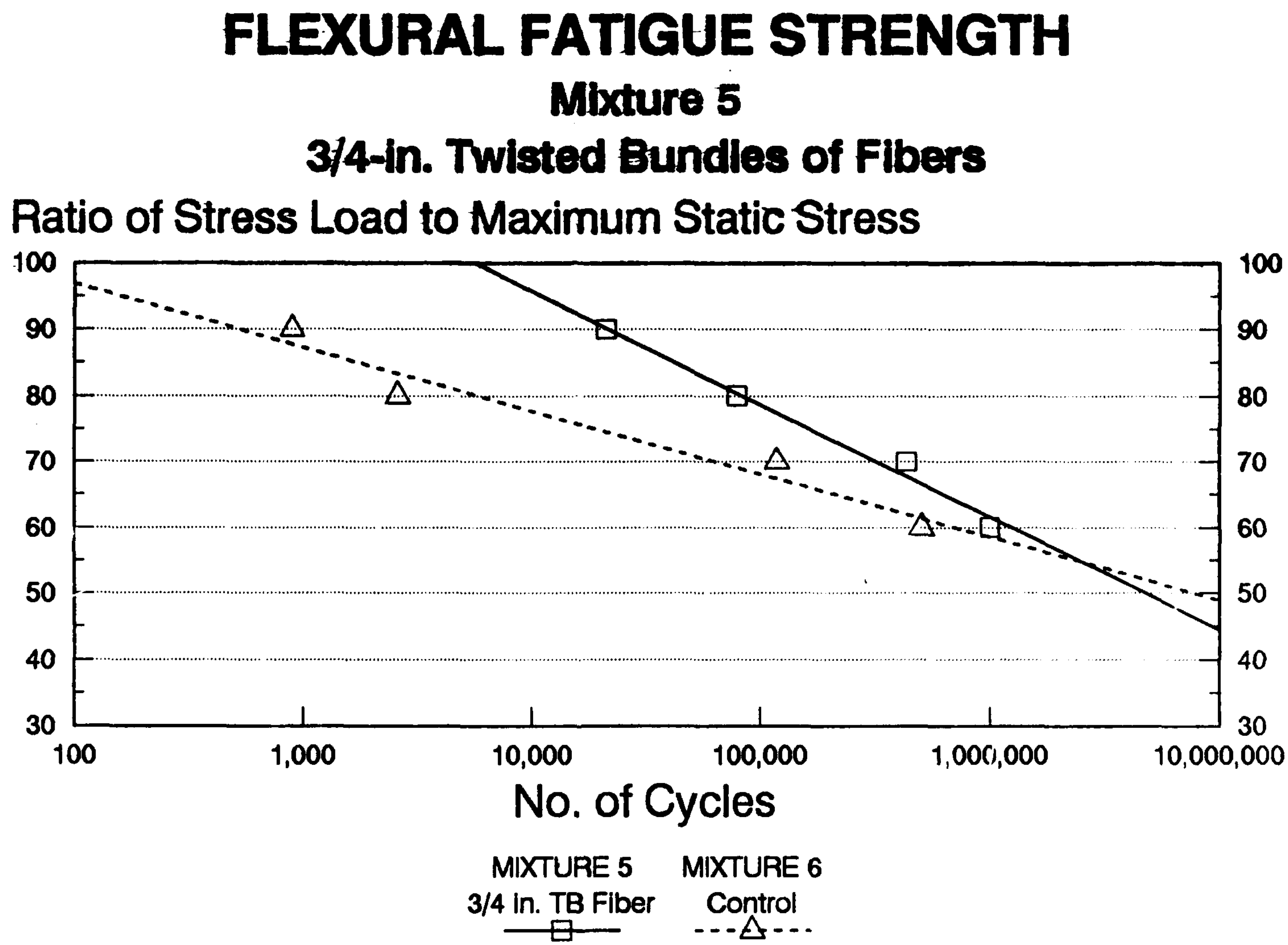


Figure 26. Fatigue curve for mixture 5

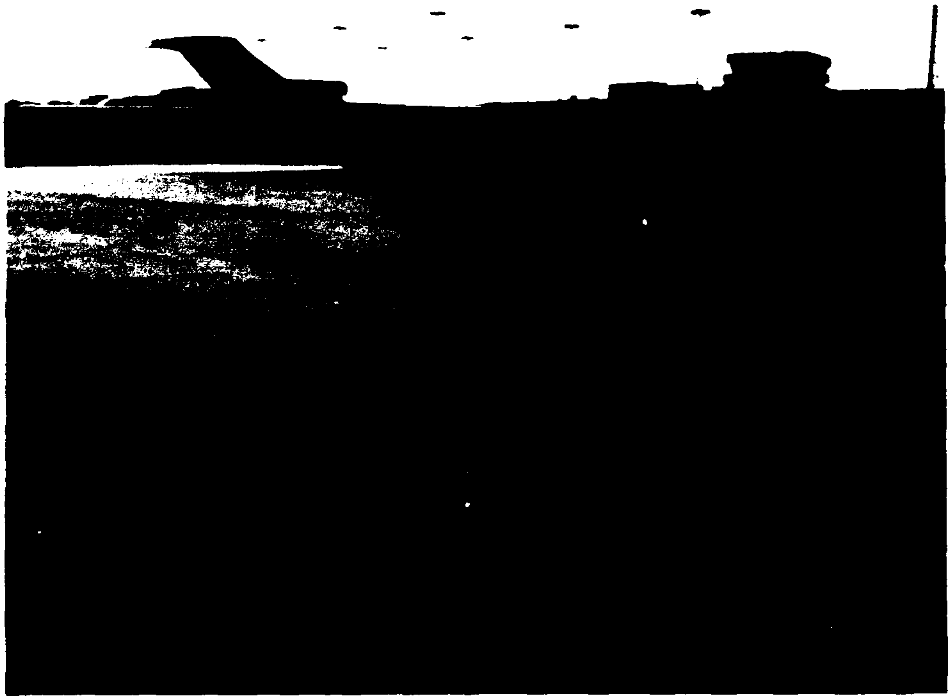


Figure 27. PFRC apron at Lambert-St. Louis International Airport

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APPENDIX A

STATISTICAL ANALYSIS

INTRODUCTION

In order to determine how well the polypropylene fibers affected and enhanced the physical and mechanical properties of a portland cement concrete mixture for a pavement application, concrete mixtures were developed with very similar composition and a standard slump requirement with varying polypropylene fiber types and fiber lengths. Each mixture was replicated once and subjected to a series of physical and mechanical tests as freshly mixed concrete and as hardened concrete specimens. An analysis of variance (ANOVA) was used to test the hypotheses and judge the differences among the different mixtures, different fiber types, and different fiber lengths. Duncan's Multiple Range Test was used to judge the significant differences and to compare all the different test results.

The results of the ANOVA of each individual test parameter for mixture types, fiber types, and fiber lengths are listed below. Tables A-1 through A-14 shows Duncan's grouping for Mixture Types; Tables A-15 through A-28 shows Duncan's grouping for Fiber Types; and Tables A-29 through A-42 shows Duncan's grouping for Fiber Lengths.

TABLE A-1

Analysis of Variance Procedure: Mixture Type

Duncan's Multiple Range Test: 7-day Compressive Strength

Means with the same letter are not significantly different.

Duncan Grouping	Mean	N	Mixture
A	3620.0	2	5
A			
A	3542.5	2	6
A			
A	3245.0	2	3
A			
A	3210.0	2	1
A			
A	3132.5	2	4
A			
A	3075.0	2	2

TABLE A-2

Analysis of Variance Procedure: Mixture Type

Duncan's Multiple Range Test: 28-day Compressive Strength

Means with the same letter are not significantly different.

Duncan Grouping	Mean	N	Mixture
A	4602.5	2	5
A			
A	4330.0	2	1
A			
A	4327.5	2	6
A			
A	4265.0	2	4
A			
A	4110.0	2	3
A			
A	4067.5	2	2

TABLE A-3

Analysis of Variance Procedure: Mixture Type

Duncan's Multiple Range Test: 7-day Flexural Strength

Means with the same letter are not significantly different.

Duncan Grouping	Mean	N	Mixture
A	621.25	2	6
A			
A	614.25	2	3
A			
A	607.50	2	5
A			
A	581.25	2	1
A			
A	573.75	2	4
A			
A	560.00	2	2

TABLE A-4

Analysis of Variance Procedure: Mixture Type

Duncan's Multiple Range Test: 28-day Flexural Strength

Means with the same letter are not significantly different.

Duncan Grouping		Mean	N	Mixture
A		721.25	2	5
A				
A	B	677.50	2	6
A	B			
A	B	672.50	2	4
A	B			
A	B	656.25	2	1
	B			
	B	632.50	2	3
	B			
	B	612.50	2	2

TABLE A-5

Analysis of Variance Procedure: Mixture Type

Duncan's Multiple Range Test: 7-day Bond Strength

Means with the same letter are not significantly different.

Duncan Grouping		Mean	N	Mixture
A		1991.2	2	6
A				
A		1837.5	2	1
A				
A		1832.5	2	3
A				
A		1730.0	2	2
A				
A		1702.5	2	5
	B	1366.2	2	4

TABLE A-6

Analysis of Variance Procedure: Mixture Type

Duncan's Multiple Range Test: 28-day Bond Strength

Means with the same letter are not significantly different.

Duncan Grouping	Mean	N	Mixture
A	2337.5	2	6
A			
A	2165.0	2	5
A			
A	2126.3	2	4
A			
A	2053.8	2	2
A			
A	2000.0	2	3
A			
A	1890.0	2	1

TABLE A-7

Analysis of Variance Procedure: Mixture Type

Duncan's Multiple Range Test: 7-day First Crack Strength

Means with the same letter are not significantly different.

Duncan Grouping			Mean	N	Mixture
A			705.00	2	5
	B		563.75	2	6
	B				
	B		558.75	2	4
	B				
	B		522.50	2	2
	B				
	B	C	488.75	2	3
		C			
		C	397.50	1	1

TABLE A-8

Analysis of Variance Procedure: Mixture Type

Duncan's Multiple Range Test: 28-day First Crack Strength

Means with the same letter are not significantly different.

Duncan Grouping	Mean	N	Mixture
A	668.75	2	5
A			
A	657.50	2	6
A			
A	648.75	2	3
A			
A	615.00	2	1
A			
A	563.75	2	2
A			
A	547.50	1	4

TABLE A-9

Analysis of Variance Procedure: Mixture Type

Duncan's Multiple Range Test: 7-day Toughness

Means with the same letter are not significantly different.

Duncan Grouping		Mean	N	Mixture
A		136.32	2	5
A				
A	B	97.05	2	2
A	B			
A	B	86.57	2	4
	B			
	B	82.65	2	6
	B			
	B	77.62	2	3
	B			
	B	51.60	1	1

TABLE A-10

Analysis of Variance Procedure: Mixture Type

Duncan's Multiple Range Test: 28-day Toughness

Means with the same letter are not significantly different.

Duncan Grouping		Mean	N	Mixture
A		121.90	2	1
A				
A	B	86.32	2	6
A	B			
A	B	74.43	2	5
A	B			
A	B	71.18	2	3
	B			
	B	62.57	2	2
	B			
	B	51.10	1	4

TABLE A-11

Analysis of Variance Procedure: Mixture Type

Duncan's Multiple Range Test: 7-day Toughness Index I5

Means with the same letter are not significantly different.

Duncan Grouping		Mean	N	Mixture
A		2.300	1	1
	B	1.450	2	2
	B			
	B	1.425	2	4
	B			
	B	1.350	2	3
	B			
	B	1.350	1	5
	B			
	B	1.200	2	6

TABLE A-12

Analysis of Variance Procedure: Mixture Type

Duncan's Multiple Range Test: 28-day Toughness Index I5

Means with the same letter are not significantly different.

Duncan Grouping			Mean	N	Mixture
A			1.700	1	4
A					
A	B		1.625	2	3
A	B				
A	B		1.475	2	5
A	B				
A	B		1.475	2	2
	B				
	B	C	1.350	2	1
		C			
		C	1.100	2	6

TABLE A-13

Analysis of Variance Procedure: Mixture Type

Duncan's Multiple Range Test: 7-day Toughness Index I10

Means with the same letter are not significantly different.

Duncan Grouping		Mean	N	Mixture
A		3.350	1	1
	B	1.875	2	2
	B			
	B	1.850	2	4
	B			
	B	1.675	2	3
	B			
	B	1.600	1	5
	B			
	B	1.300	2	6

TABLE A-14

Analysis of Variance Procedure: Mixture Type

Duncan's Multiple Range Test: 28-day Toughness Index I10

Means with the same letter are not significantly different.

Duncan Grouping			Mean	N	Mixture
A			2.300	1	4
A					
A	B		1.900	2	5
A	B				
A	B		1.900	2	3
A	B				
A	B		1.900	2	2
	B				
	B	C	1.500	2	1
		C			
		C	1.125	2	6

TABLE A-15

Analysis of Variance Procedure: Fiber Type

Duncan's Multiple Range Test: 7-day Compressive Strength

Means with the same letter are not significantly different.

Duncan Grouping	Mean	N	Fiber Type
A	3542.5	2	NONE
A			
A	3376.3	4	TB
A			
A	3210.0	2	MONO
A			
A	3160.0	4	CF

TABLE A-16

Analysis of Variance Procedure: Fiber Type

Duncan's Multiple Range Test: 28-day Compressive Strength

Means with the same letter are not significantly different.

Duncan Grouping	Mean	N	Fiber Type
A	4433.8	4	TB
A			
A	4330.0	2	MONO
A			
A	4327.5	2	NONE
A			
A	4088.8	4	CF

TABLE A-17

Analysis of Variance Procedure: Fiber Type

Duncan's Multiple Range Test: 7-day Flexural Strength

Means with the same letter are not significantly different.

Duncan Grouping	Mean	N	Fiber Type
A	621.25	2	NONE
A			
A	590.62	4	TB
A			
A	587.12	4	CF
A			
A	581.25	2	MONO

TABLE A-18

Analysis of Variance Procedure: Fiber Type

Duncan's Multiple Range Test for variable: 28-day Flexural Strength

Means with the same letter are not significantly different.

Duncan Grouping		Mean	N	Fiber Type
A		696.87	4	TB
A				
A	B	677.50	2	NONE
A	B			
A	B	656.25	2	MONO
	B			
	B	622.50	4	CF

TABLE A-19

Analysis of Variance Procedure: Fiber Type

Duncan's Multiple Range Test: 7-day Bond Strength

Means with the same letter are not significantly different.

Duncan Grouping		Mean	N	Fiber Type
A		1991.2	2	NONE
A				
A	B	1837.5	2	MONO
A	B			
A	B	1781.2	4	CF
	B			
	B	1534.4	4	TB

TABLE A-20

Analysis of Variance Procedure: Fiber Type

Duncan's Multiple Range Test: 28-days Bond Strength

Means with the same letter are not significantly different.

Duncan Grouping		Mean	N	Fiber Type
A		2337.5	2	NONE
A				
A	B	2145.6	4	TB
A	B			
A	B	2026.9	4	CF
	B			
	B	1890.0	2	MONO

TABLE A-21

Analysis of Variance Procedure: Fiber Type

Duncan's Multiple Range Test: 7-day First Crack Strength

Means with the same letter are not significantly different.

Duncan Grouping		Mean	N	Fiber Type
A		631.87	4	TB
A				
A		563.75	2	NONE
A				
A	B	505.62	4	CF
	B			
	B	397.50	1	MONO

TABLE A-22

Analysis of Variance Procedure: Fiber Type

Duncan's Multiple Range Test: 28-day First Crack Strength

Means with the same letter are not significantly different.

Duncan Grouping	Mean	N	Fiber Type
A	657.50	2	NONE
A			
A	628.33	3	TB
A			
A	615.00	2	MONO
A			
A	606.25	4	CF

TABLE A-23

Analysis of Variance Procedure: Fiber Type

Duncan's Multiple Range Test: 7-day Toughness

Means with the same letter are not significantly different.

Duncan Grouping	Mean	N	Fiber Type
A	111.45	4	TB
A			
A	87.34	4	CF
A			
A	82.65	2	NONE
A			
A	51.60	1	MONO

TABLE A-24

Analysis of Variance Procedure: Fiber Type

Duncan's Multiple Range Test: 28-day Toughness

Means with the same letter are not significantly different.

Duncan Grouping		Mean	N	Fiber Type
A		121.90	2	MONO
A				
A	B	86.32	2	NONE
	B			
	B	66.87	4	CF
	B			
	B	66.65	3	TB

TABLE A-25

Analysis of Variance Procedure: Fiber Type

Duncan's Multiple Range Test: 7-day Toughness Index I5

Means with the same letter are not significantly different.

Duncan Grouping		Mean	N	Fiber Type
A		2.300	1	MONO
	B	1.400	3	TB
	B			
	B	1.400	4	CF
	B			
	B	1.200	2	NONE

TABLE A-26

Analysis of Variance Procedure: Fiber Type

Duncan's Multiple Range Test: 28-day Toughness Index I5

Means with the same letter are not significantly different.

Duncan Grouping		Mean	N	Fiber Type
A		1.550	3	TB
A				
A		1.550	4	CF
A				
A	B	1.350	2	MONO
	B			
	B	1.100	2	NONE

TABLE A-27

Analysis of Variance Procedure: Fiber Type

Duncan's Multiple Range Test: 7-day Toughness I10

Means with the same letter are not significantly different.

Duncan Grouping		Mean	N	Fiber Type
A		3.350	1	MONO
	B	1.775	4	CF
	B			
	B	1.767	3	TB
	B			
	B	1.300	2	NONE

TABLE A-28

Analysis of Variance Procedure: Fiber Type

Duncan's Multiple Range Test: 28-day Toughness I10

Means with the same letter are not significantly different.

Duncan Grouping		Mean	N	Fiber Type
A		2.033	3	TB
A				
A		1.900	4	CF
	B	1.500	2	MONO
	B			
	B	1.125	2	NONE

TABLE A-29

Analysis of Variance Procedure: Fiber Length

Duncan's Multiple Range Test: 7-day Compressive Strength

Means with the same letter are not significantly different.

Duncan Grouping	Mean	N	Fiber Length
A	3432.5	4	0.75
A			
A	3103.8	4	1.5

TABLE A-30

Analysis of Variance Procedure: Fiber Length

Duncan's Multiple Range Test: 28-day Compressive Strength

Means with the same letter are not significantly different.

Duncan Grouping	Mean	N	Fiber Length
A	4356.3	4	0.75
A			
A	4166.3	4	1.5

TABLE A-31

Analysis of Variance Procedure: Fiber Length

Duncan's Multiple Range Test: 7-day Flexural Strength

Means with the same letter are not significantly different.

Duncan Grouping	Mean	N	Fiber Length
A	610.87	4	0.75
A			
A	566.87	4	1.5

TABLE A-32

Analysis of Variance Procedure: Fiber Length

Duncan's Multiple Range Test: 28-day Flexural Strength

Means with the same letter are not significantly different.

Duncan Grouping	Mean	N	Fiber Length
A	676.87	4	0.75
A			
A	642.50	4	1.5

TABLE A-33

Analysis of Variance Procedure: Fiber Length

Duncan's Multiple Range Test: 7-day Bond Strength

Means with the same letter are not significantly different.

Duncan Grouping	Mean	N	Fiber Length
A	1767.50	4	0.75
A			
A	1548.13	4	1.5

TABLE A-34

Analysis of Variance Procedure: Fiber Length

Duncan's Multiple Range Test: 28-day Bond Strength

Means with the same letter are not significantly different.

Duncan Grouping	Mean	N	Fiber Length
A	2090.00	4	1.5
A			
A	2082.50	4	0.75

TABLE A-35

Analysis of Variance Procedure: Fiber Length

Duncan's Multiple Range Test: 7-day Toughness

Means with the same letter are not significantly different.

Duncan Grouping	Mean	N	Fiber Length
A	106.97	4	0.75
A			
A	91.81	4	1.5

TABLE A-36

Analysis of Variance Procedure: Fiber Length

Duncan's Multiple Range Test: 28-day Toughness

Means with the same letter are not significantly different.

Duncan Grouping	Mean	N	Fiber Length
A	72.80	4	0.75
A			
A	58.75	3	1.5

TABLE A-37

Analysis of Variance Procedure: Fiber Length

Duncan's Multiple Range Test: 7-day First Crack Strength

Means with the same letter are not significantly different.

Duncan Grouping	Mean	N	Fiber Length
A	596.87	4	0.75
A			
A	540.62	4	1.5

TABLE A-38

Analysis of Variance Procedure: Fiber Length

Duncan's Multiple Range Test: 28-day First Crack Strength

Means with the same letter are not significantly differently.

Duncan Grouping	Mean	N	Fiber Length
A	658.75	4	0.75
A			
A	558.33	3	1.5

Table A-39

Analysis of Variance Procedure: Fiber Length

Duncan's Multiple Range Test: 7-day Toughness Index I5

Means with the same letter are not significantly different.

Duncan Grouping	Mean	N	Fiber Length
A	1.437	4	1.5
A			
A	1.350	3	0.75

TABLE A-40

Analysis of Variance Procedure: Fiber Length

Duncan's Multiple Range Test: 28-day Toughness Index I5

Means with the same Letter are not significantly different.

Duncan Grouping	Mean	N	Fiber Length
A	1.5500	3	1.5
A			
A	1.5500	4	0.75

TABLE A-41

Analysis of Variance Procedure: Fiber Length

Duncan's Multiple Range Test: 7-day Toughness Index I10

Means with the same letter are not significantly different.

Duncan Grouping	Mean	N	Fiber Length
A	1.862	4	1.5
A			
A	1.650	3	0.75

TABLE A-42

Analysis of Variance Procedure: Fiber Length

Duncan's Multiple Range Test: 28-day Toughness Index I10

Means with the same letter are not significantly different.

Duncan Grouping	Mean	N	Fiber Length
A	2.0333	3	1.5
A			
A	1.9000	4	0.75

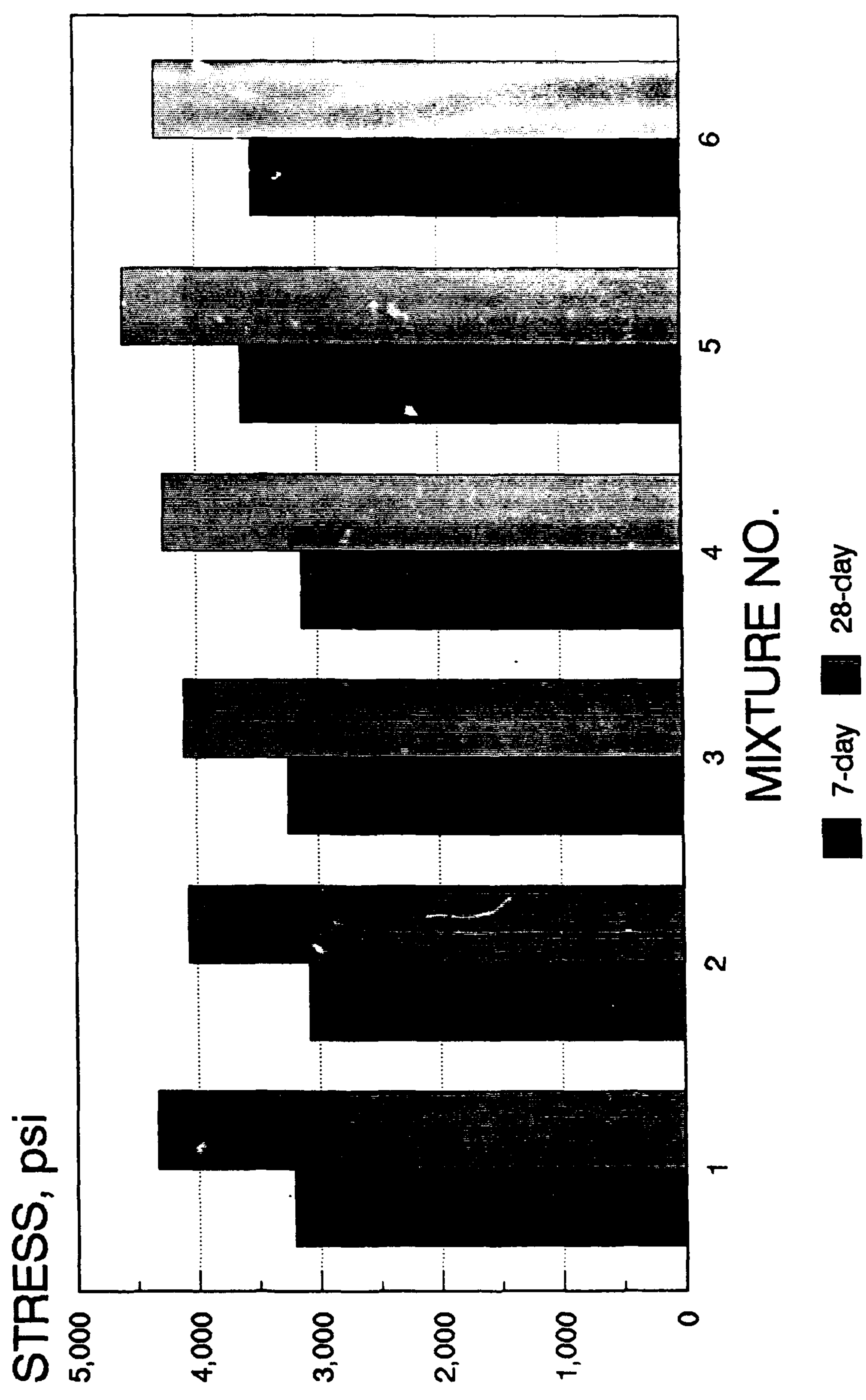
APPENDIX B

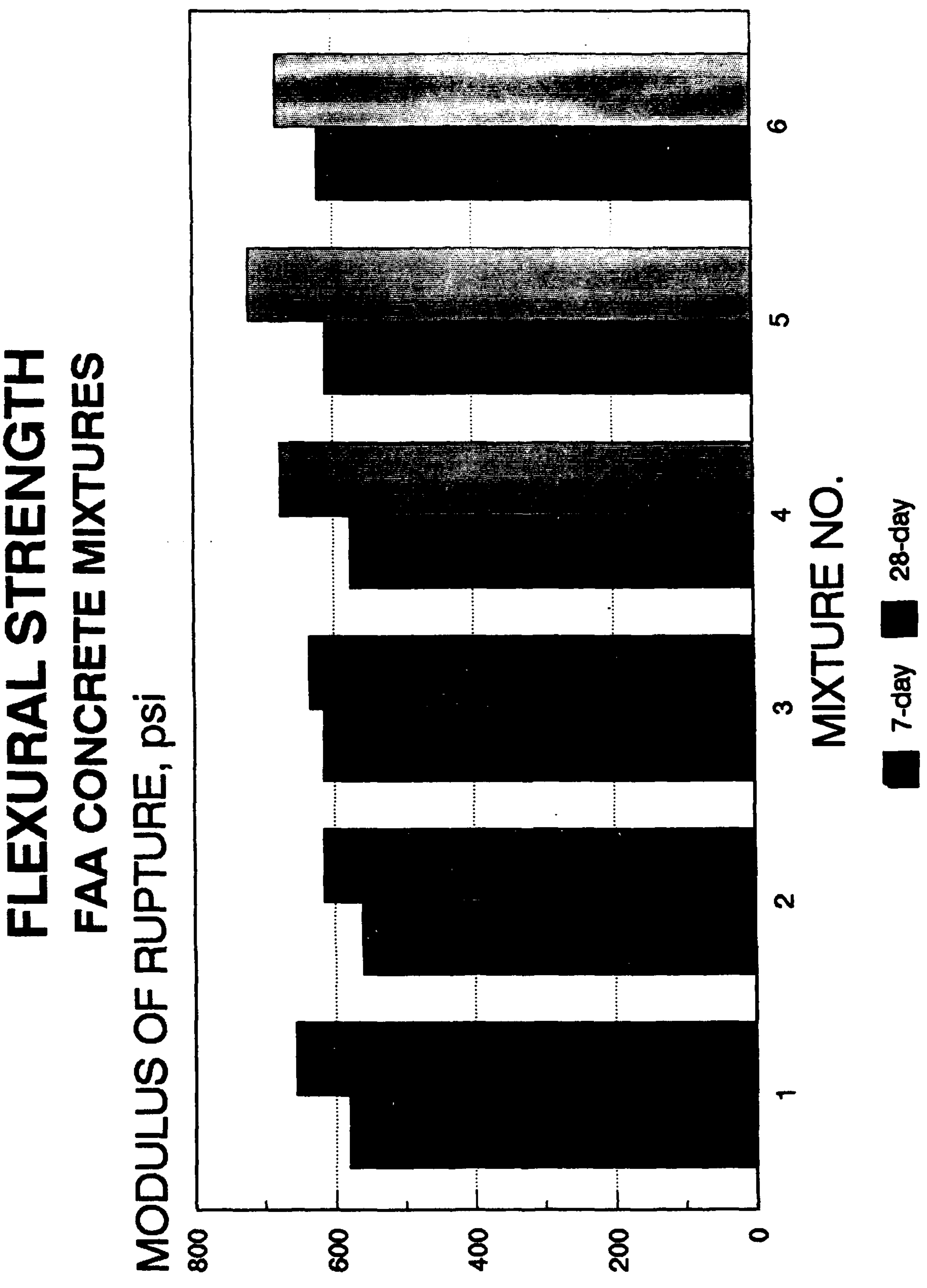
GRAPHICAL COMPARISON OF TEST PROPERTY RESULTS

INTRODUCTION

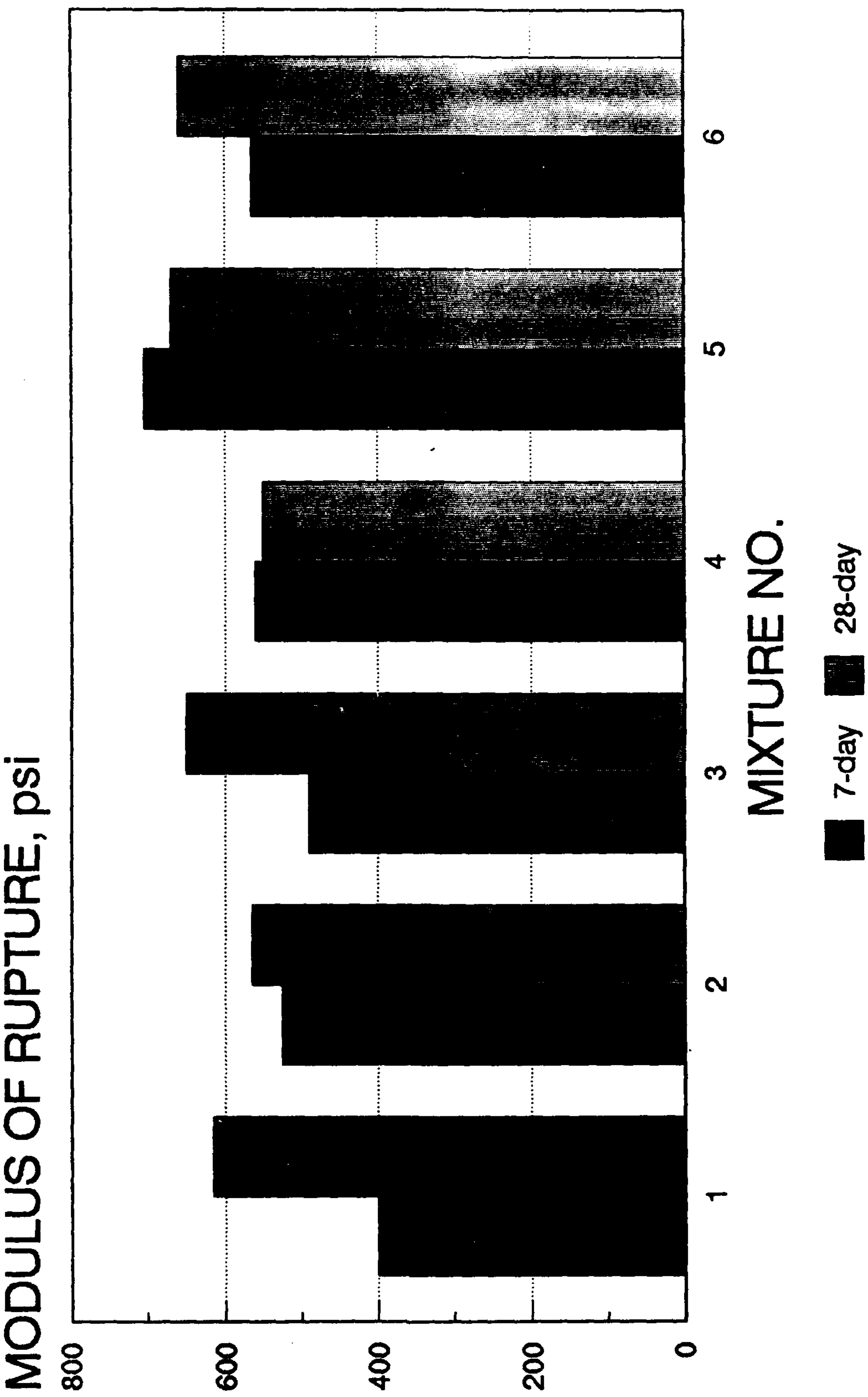
A graphical representation of the various test properties is included for improved comprehension of the laboratory test results. Pages B-2 through B-8 show a comparison of the various test properties for each mixture. Pages B-9 through B-15 show a comparison of the various test properties for each type of fiber. Pages B-16 through B-22 show a comparison of the various test properties for each length of fiber.

UNCONFINED COMPRESSIVE STRENGTH
FAA CONCRETE MIXTURES

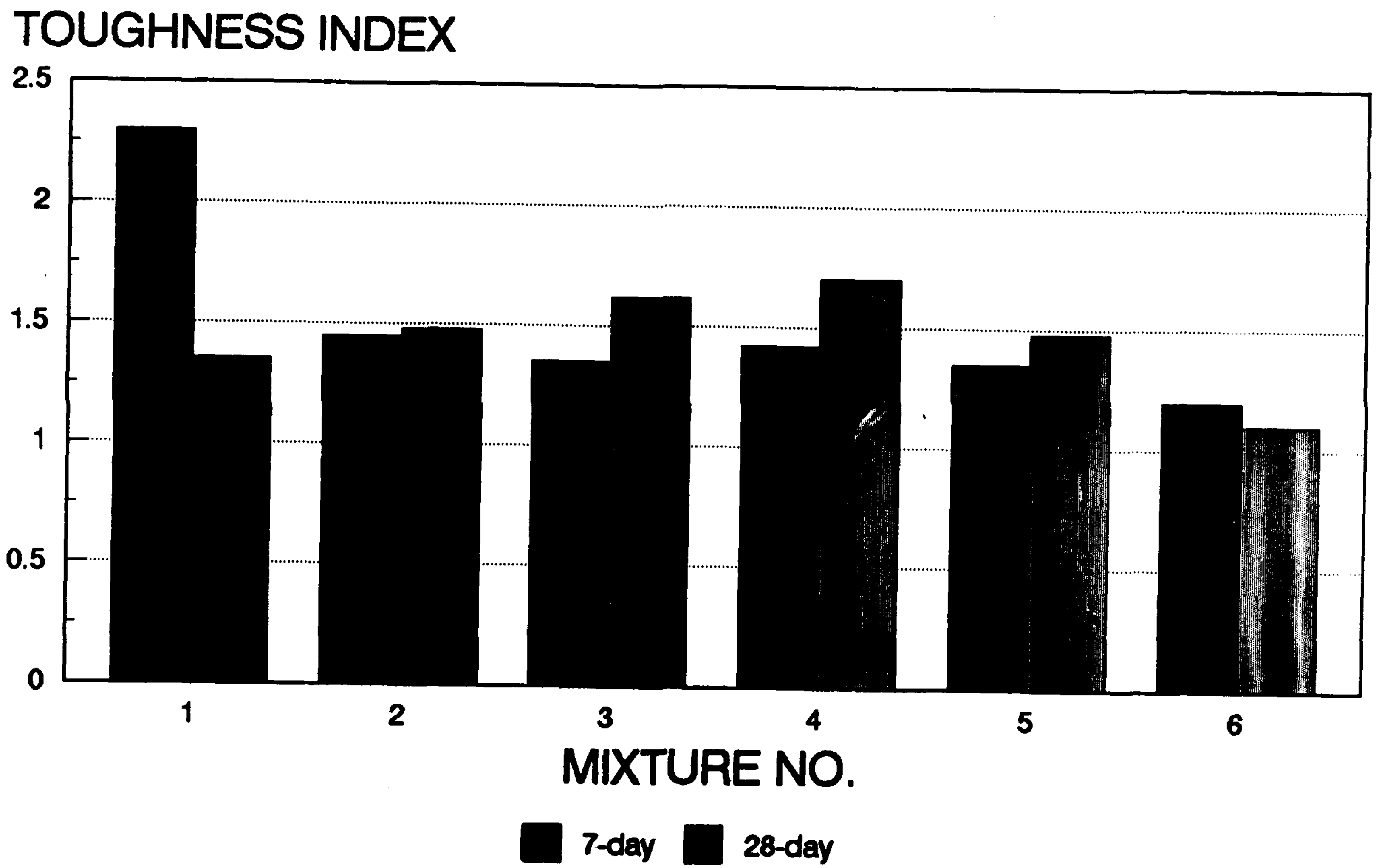



FLEXURAL STRENGTH
FAA CONCRETE MIXTURES
MODULUS OF RUPTURE, psi
800
600
400
200
0
1
2
3
4
5
6
MIXTURE NO.
7-day
28-day

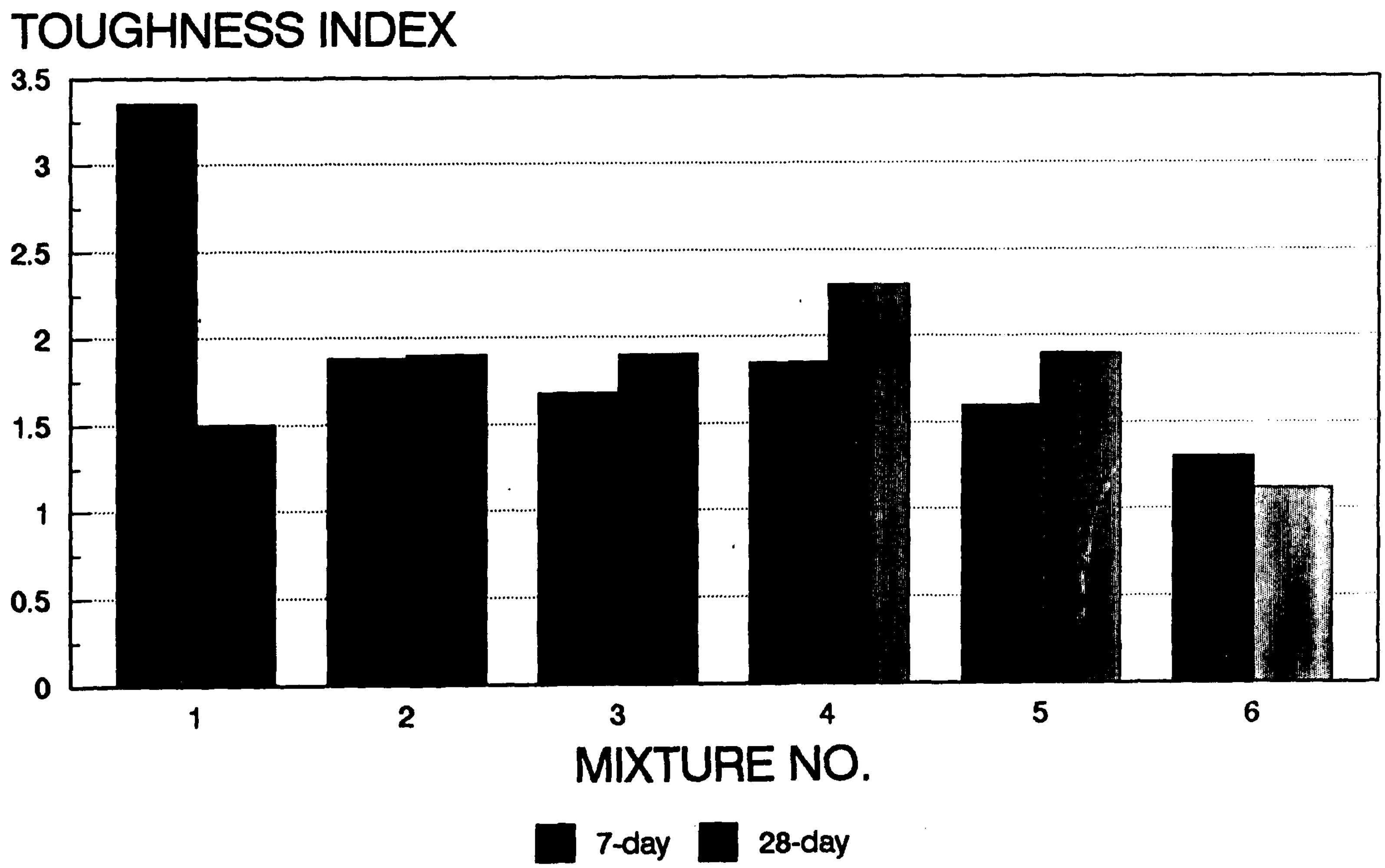
FIRST CRACK STRENGTH
FAA CONCRETE MIXTURES

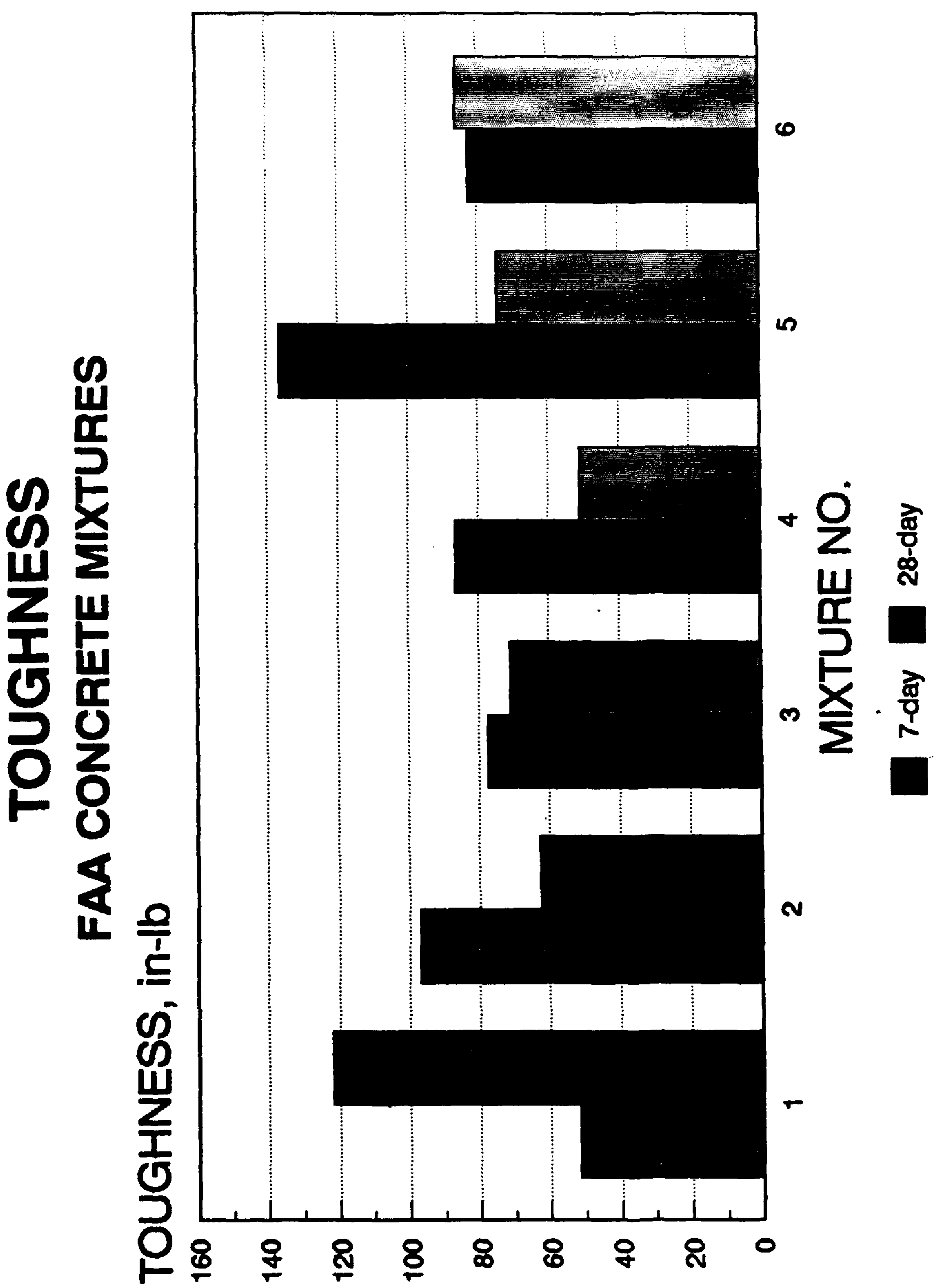


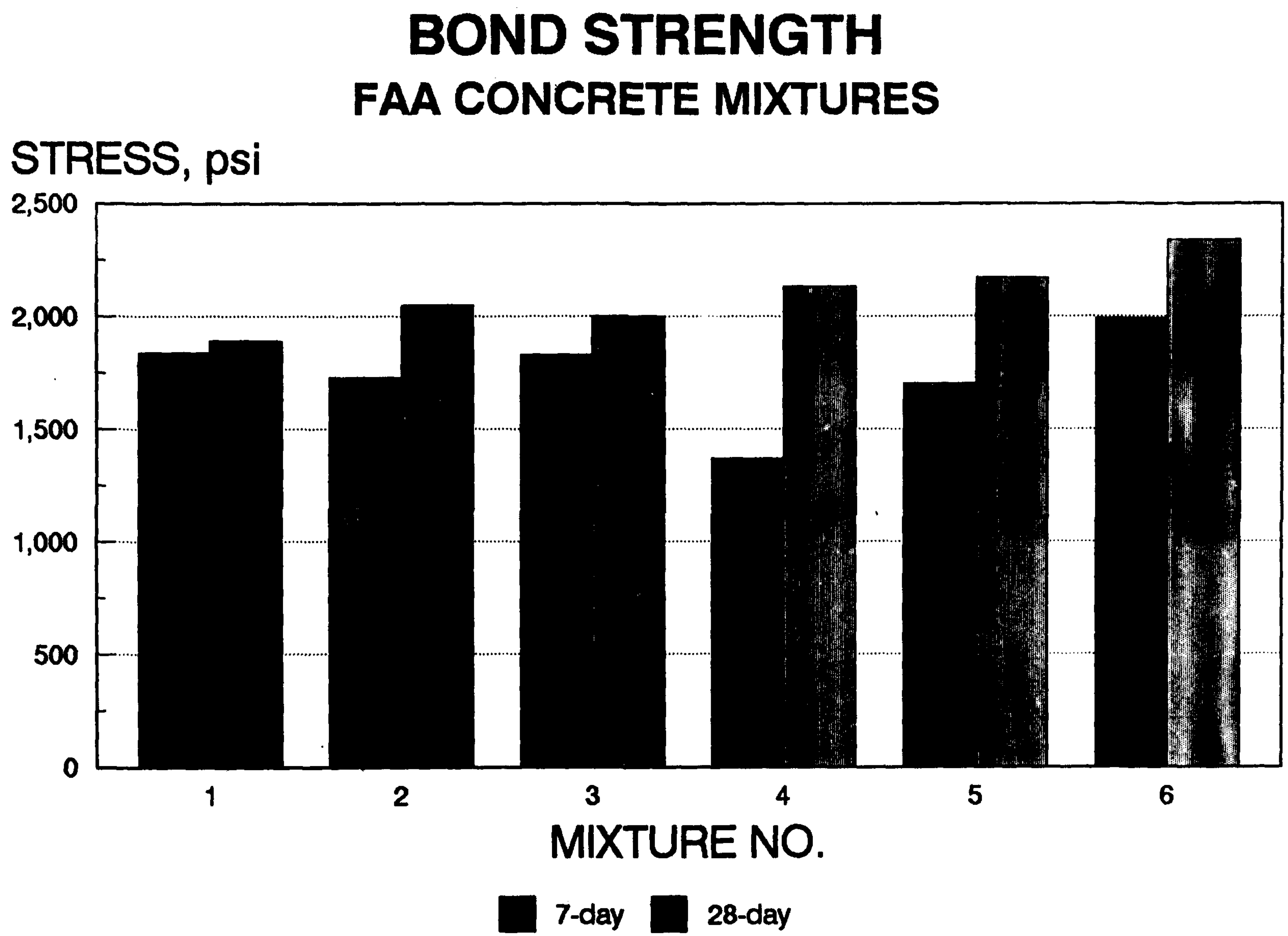
I-5 TOUGHNESS INDEX
FAA CONCRETE MIXTURES

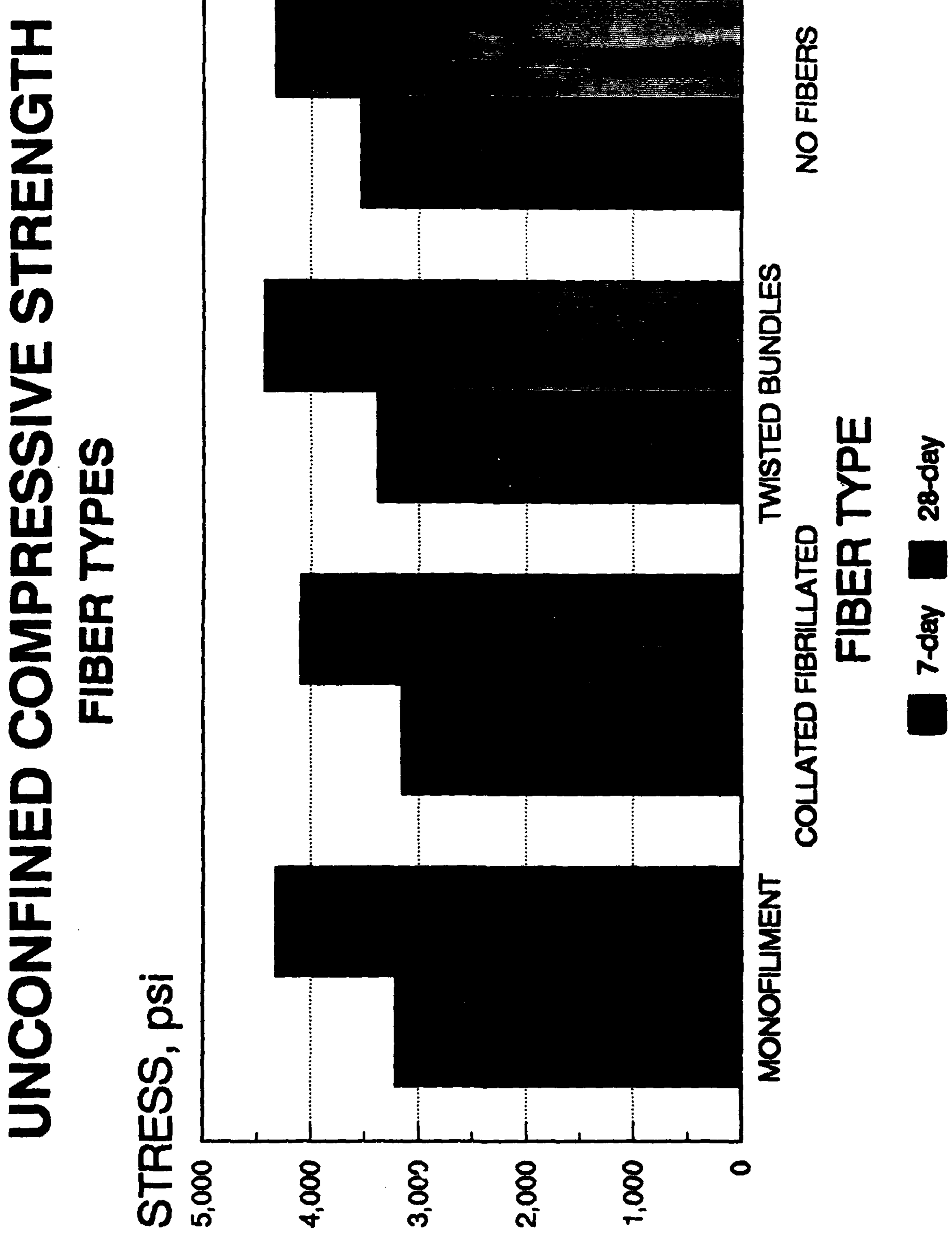


I-10 TOUGHNESS INDEX
FAA CONCRETE MIXTURES

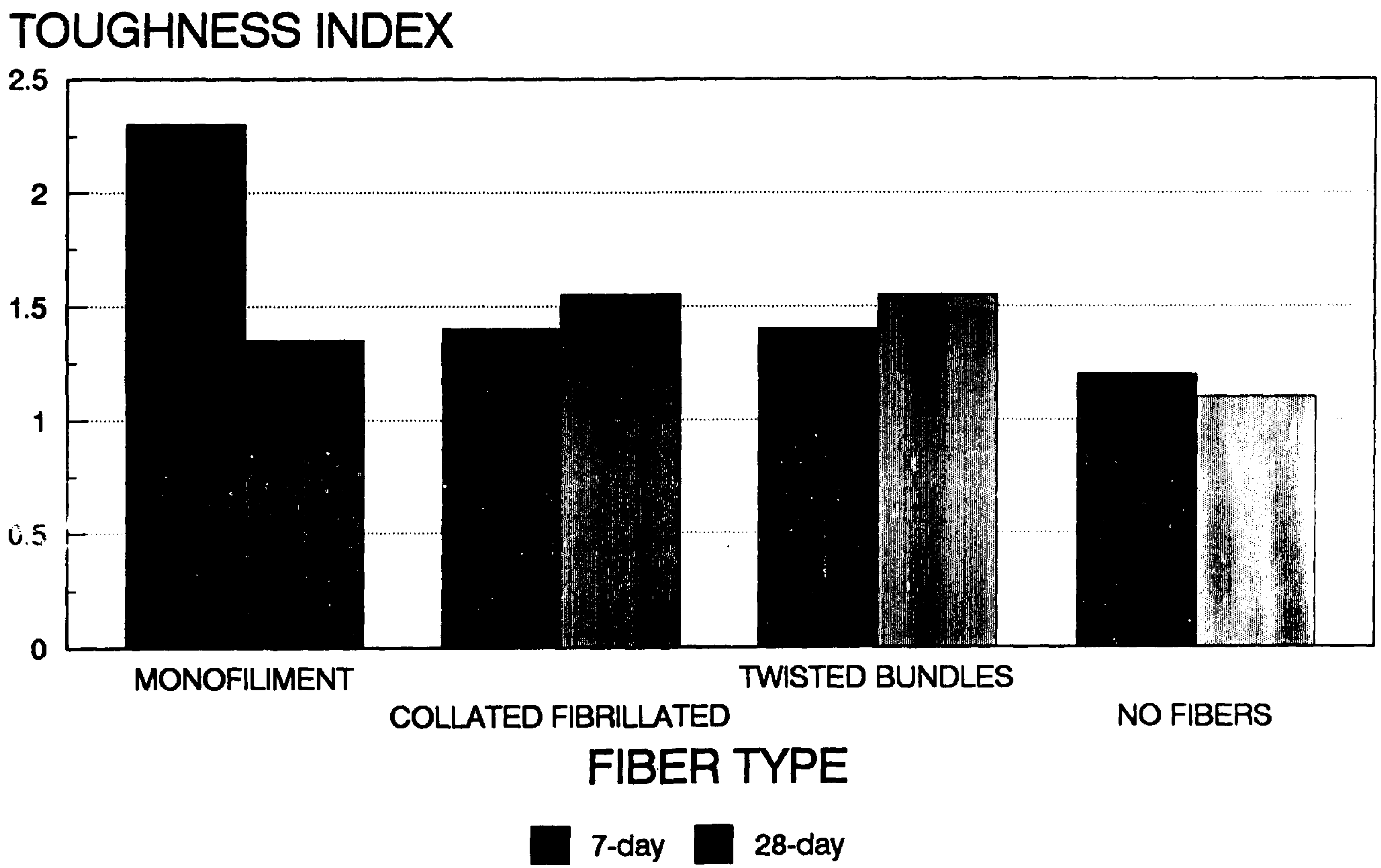


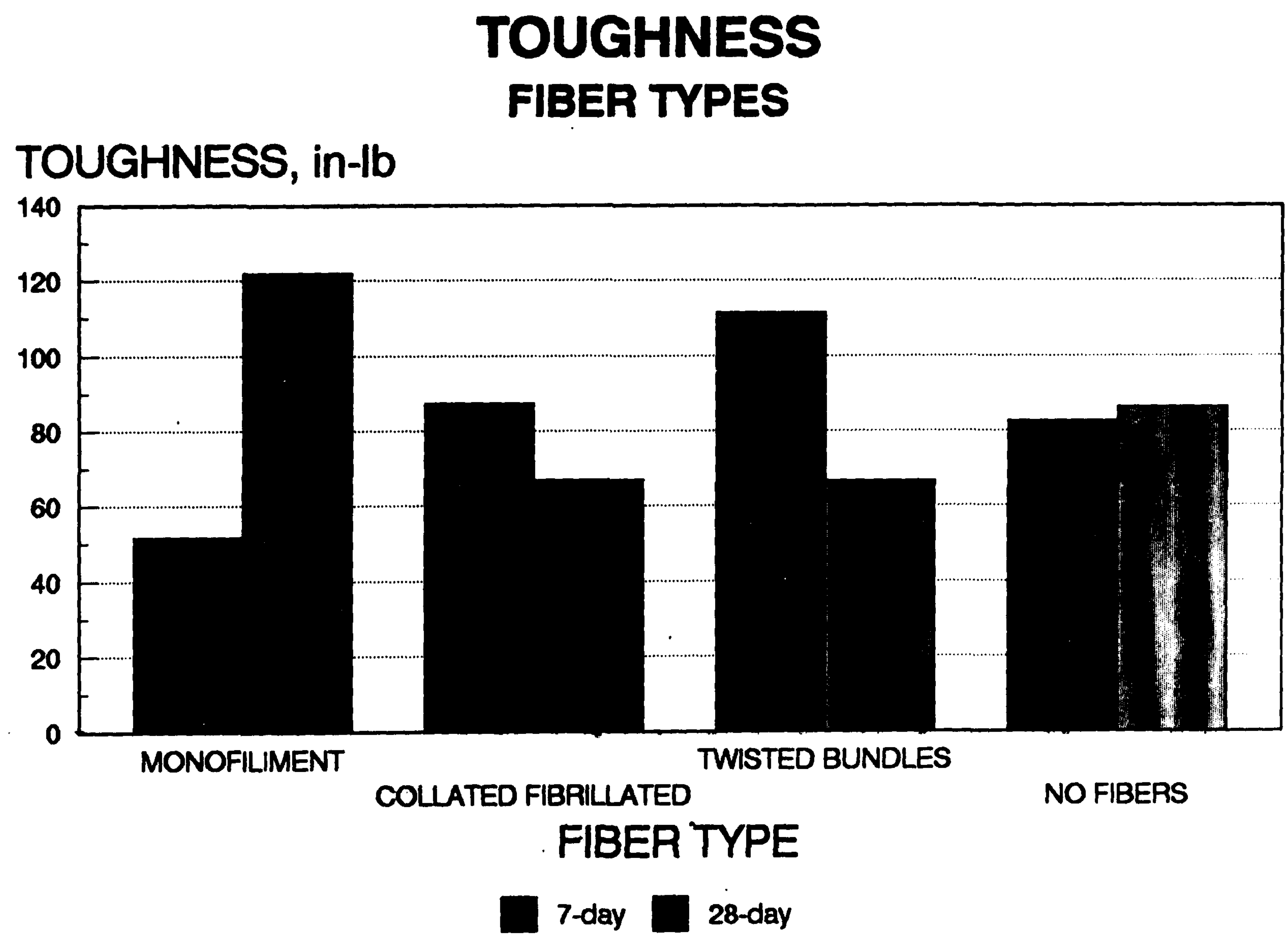

TOUGHNESS
FAA CONCRETE MIXTURES
TOUGHNESS, in-lb
160
140
120
100
80
60
40
20
0
1
2
3
4
5
6
MIXTURE NO.
7-day
28-day


BOND STRENGTH
FAA CONCRETE MIXTURES
STRESS, psi
2,500
2,000
1,500
1,000
500
0
1
2
3
4
5
6
MIXTURE NO.
7-day
28-day


UNCONFINED COMPRESSIVE STRENGTH
FIBER TYPES
STRESS, psi
5,000
4,000
3,000
2,000
1,000
0
MONOFILIMENT
COLLATED FIBRILLATED
TWISTED BUNDLES
NO FIBERS
FIBER TYPE
7-day
28-day

I-5 TOUGHNESS INDEX
FIBER TYPES

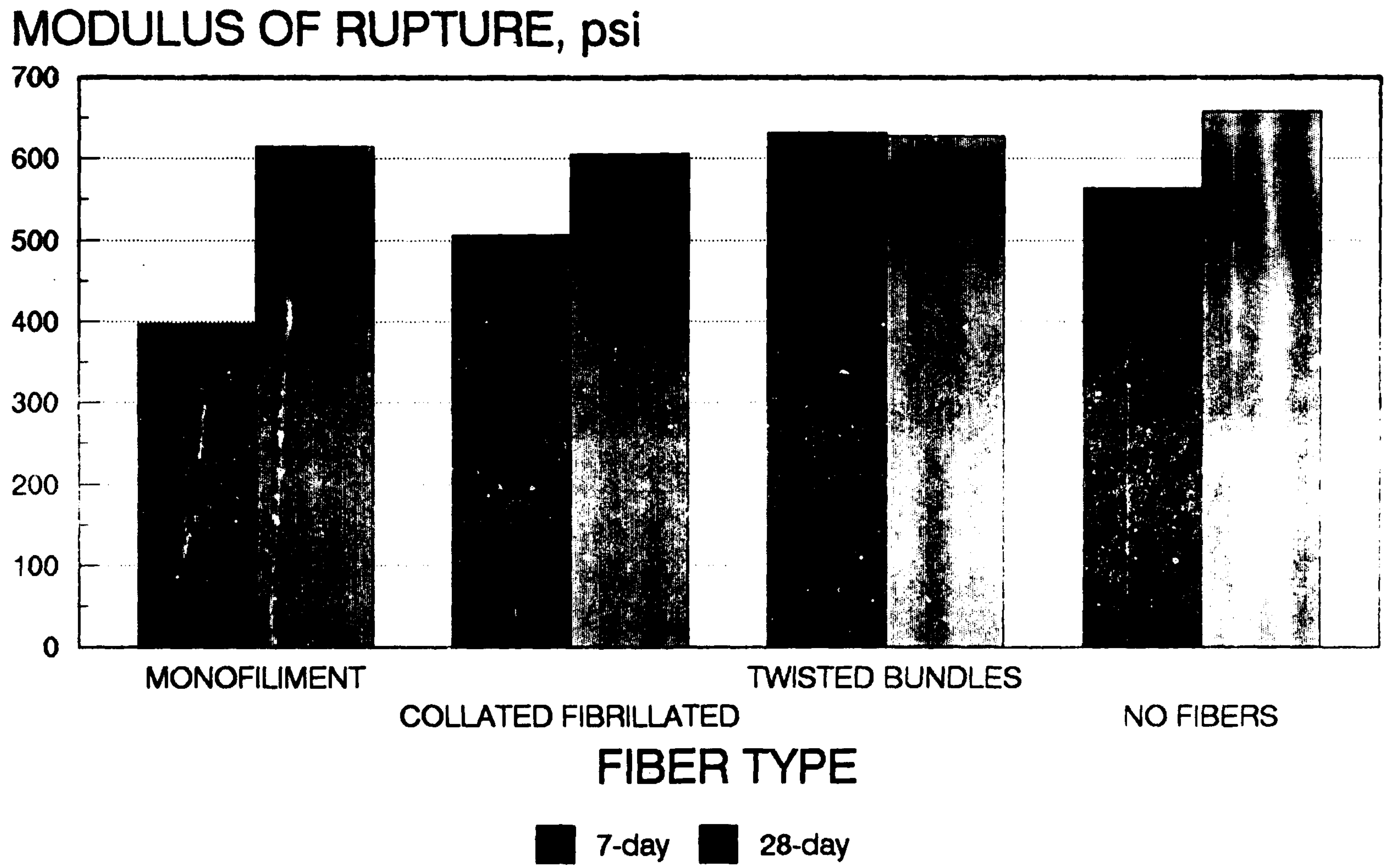




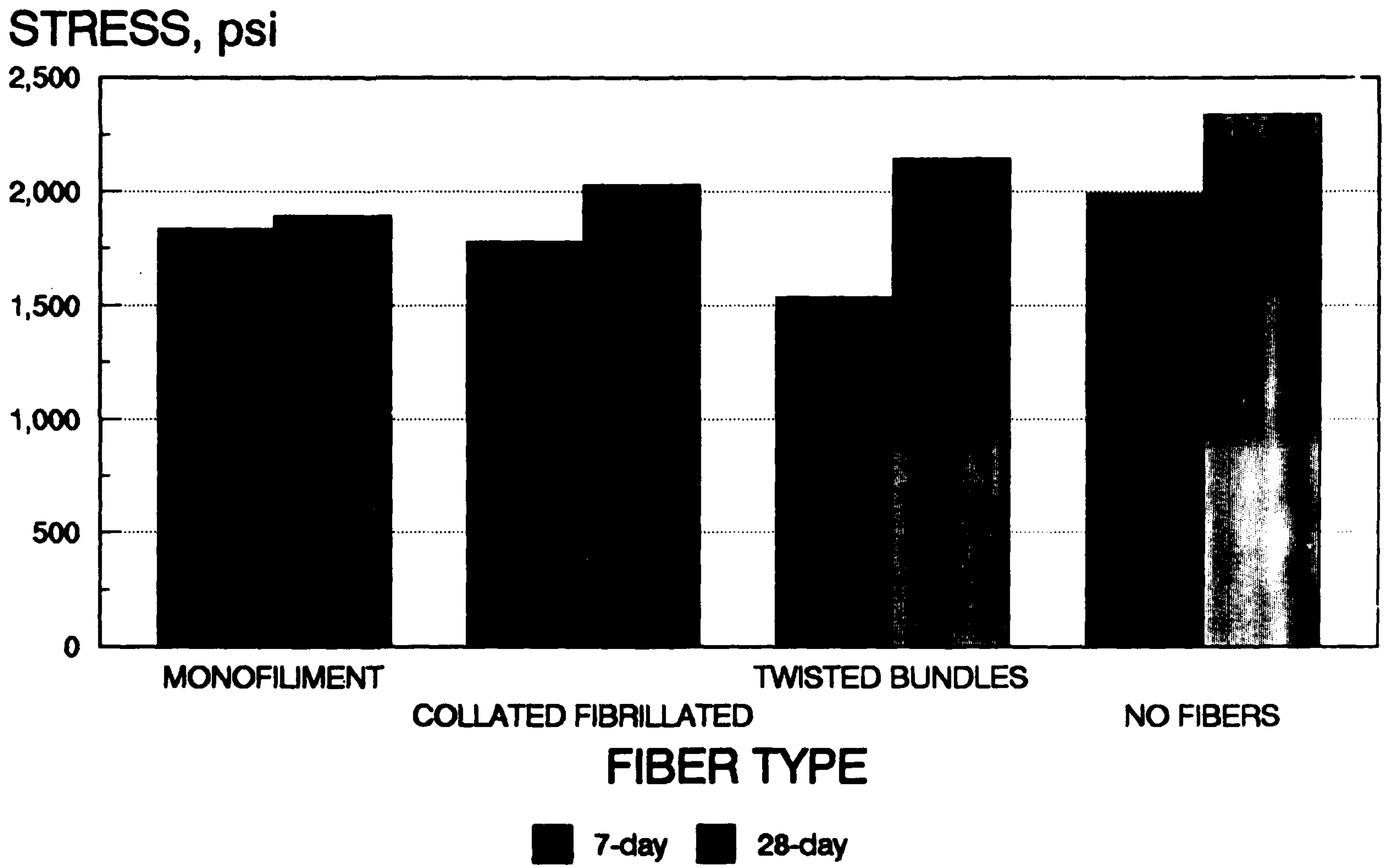
TOUGHNESS
FIBER TYPES
TOUGHNESS, in-lb
140
120
100
80
60
40
20
0
MONOFILIMENT
COLLATED FIBRILLATED
TWISTED BUNDLES
NO FIBERS
FIBER TYPE
7-day
28-day

FIRST CRACK STRENGTH

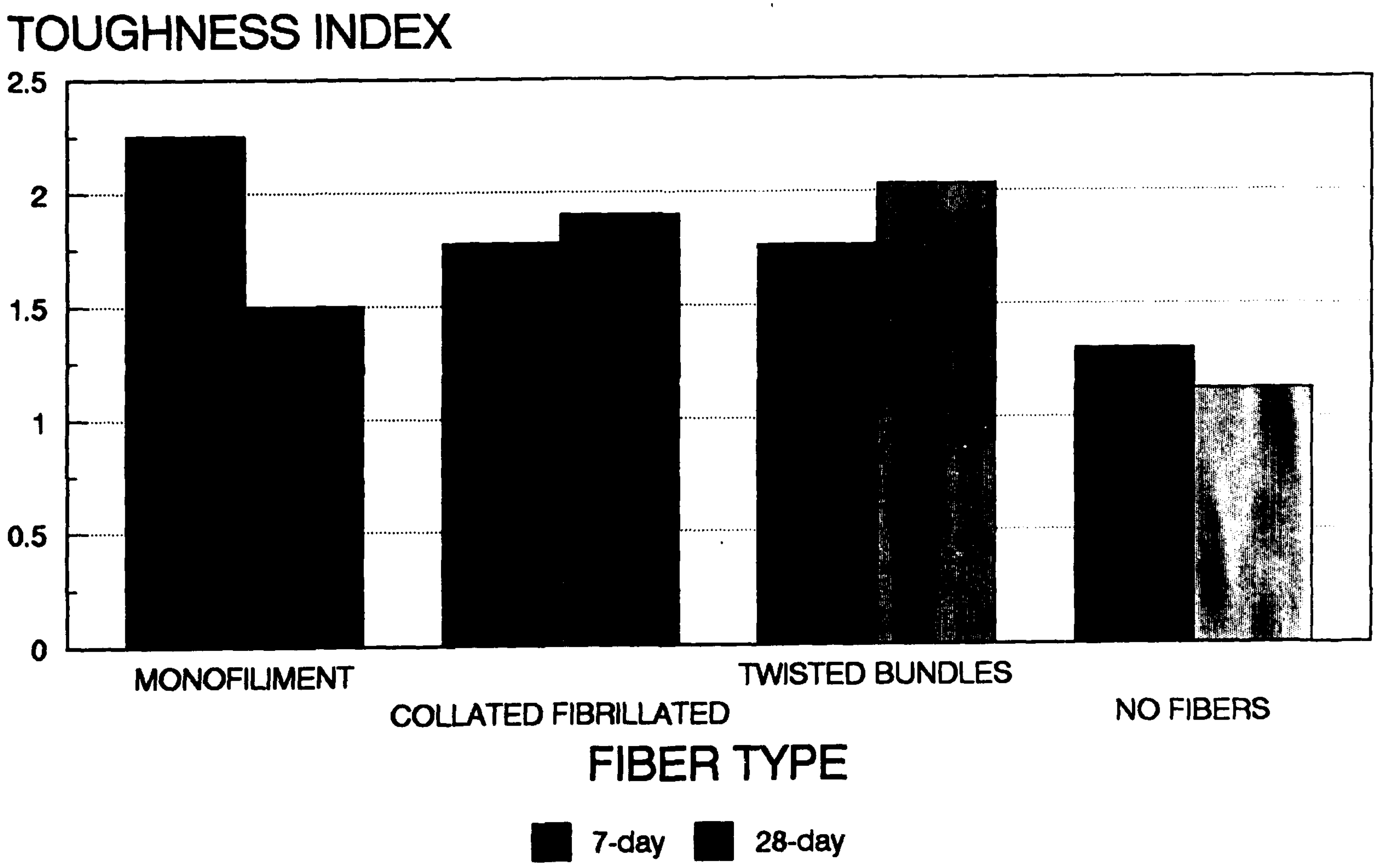
FIBER TYPES



BOND STRENGTH
FIBER TYPES

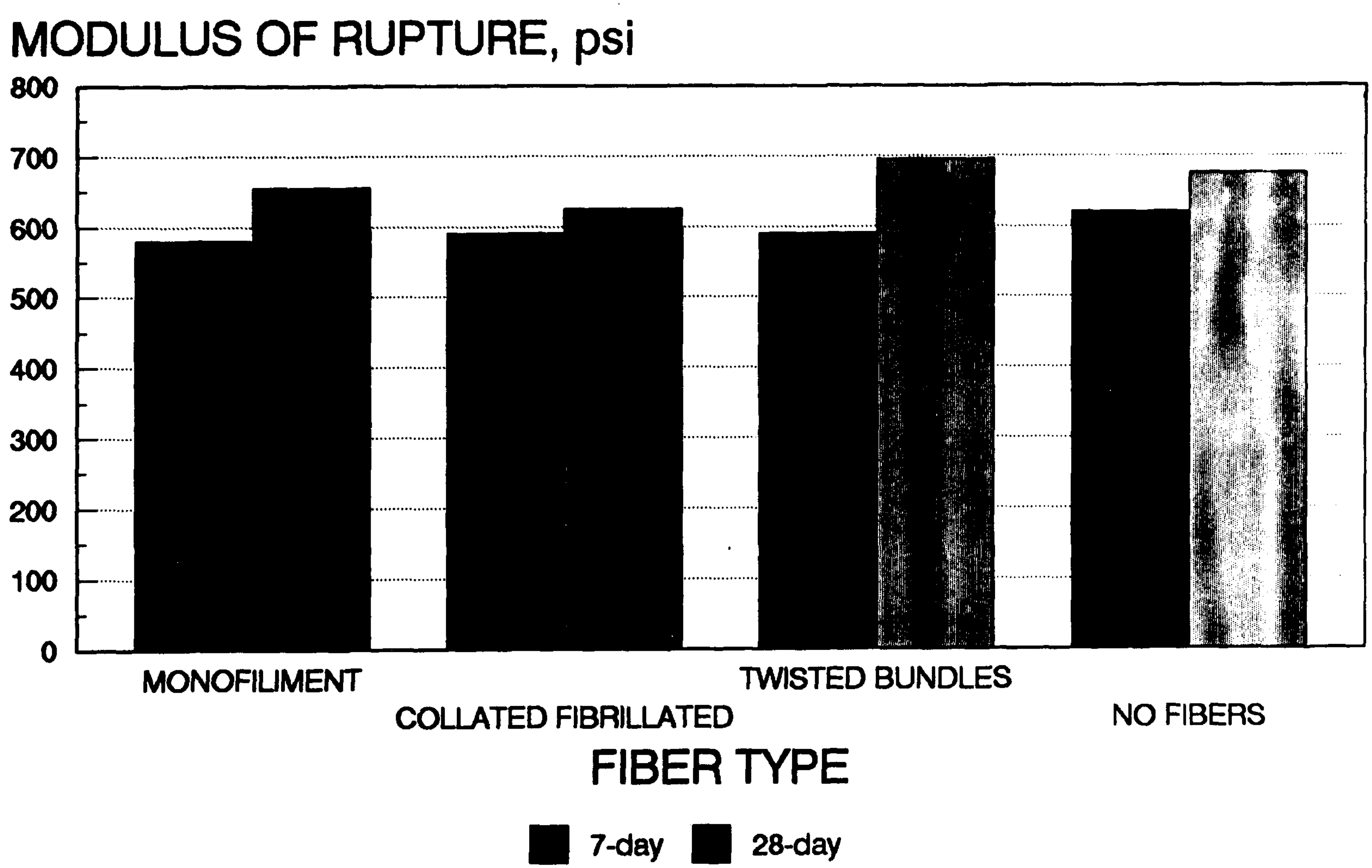


I-10 TOUGHNESS INDEX
FIBER TYPES



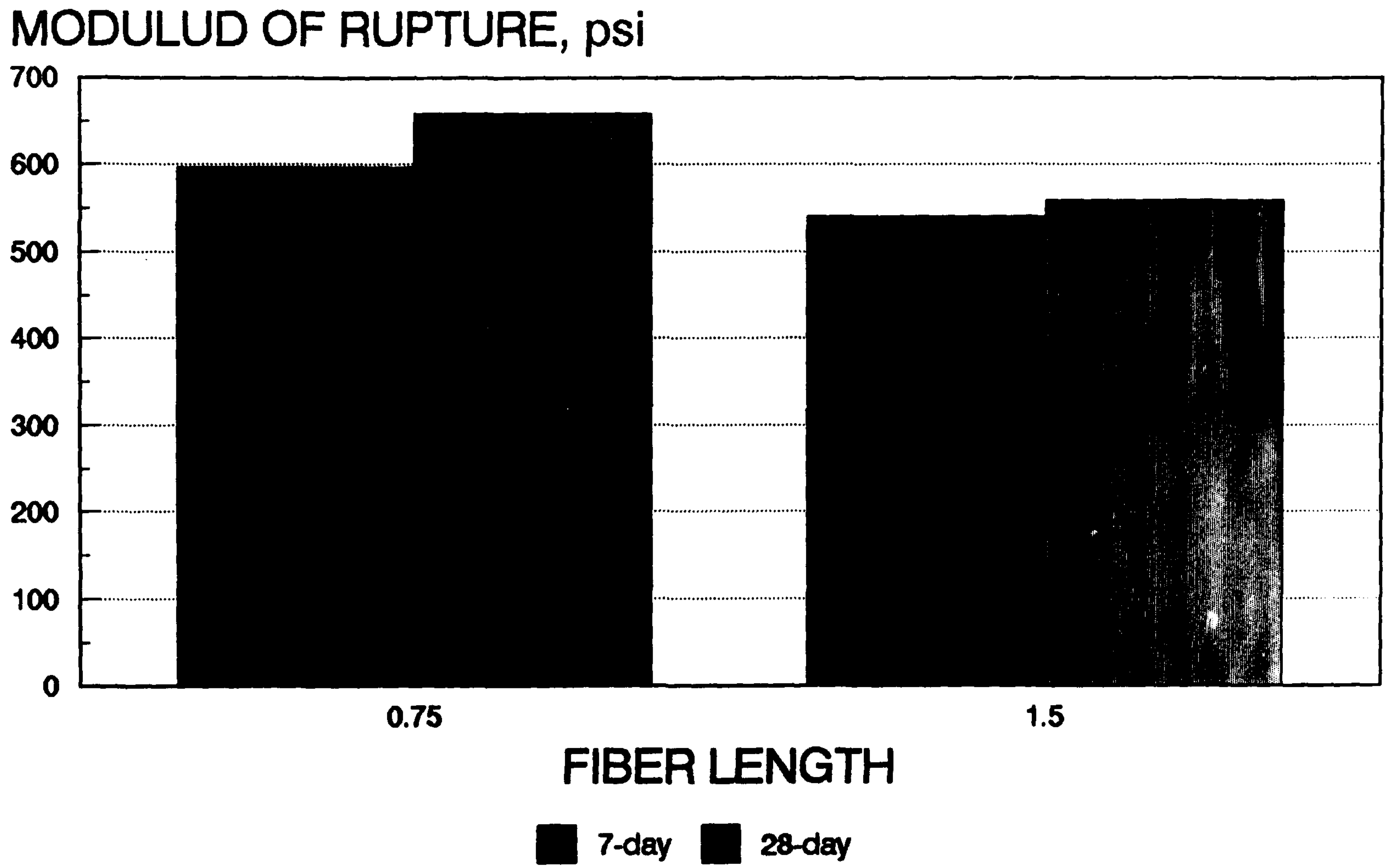
FLEXURAL STRENGTH

FIBER TYPES

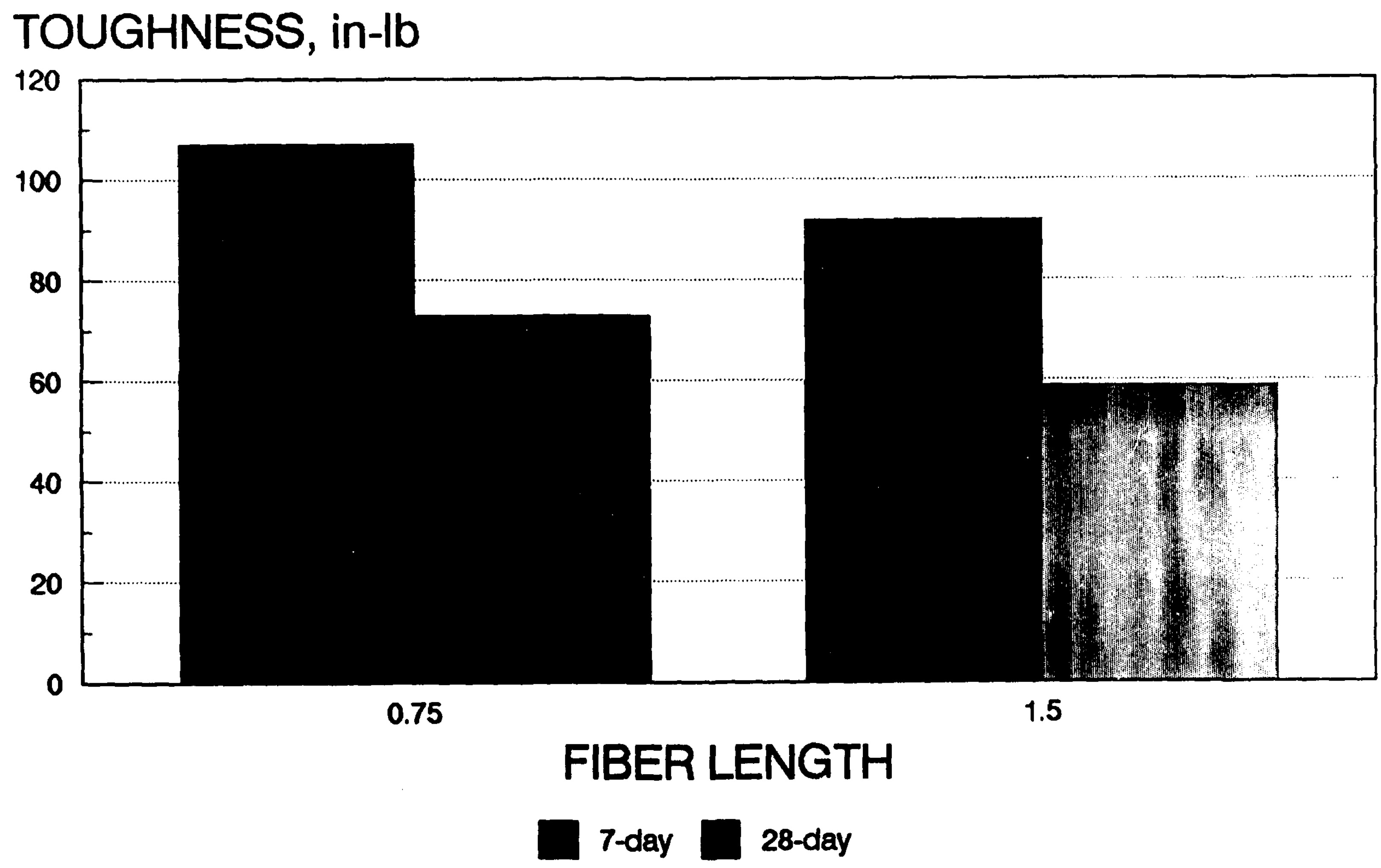


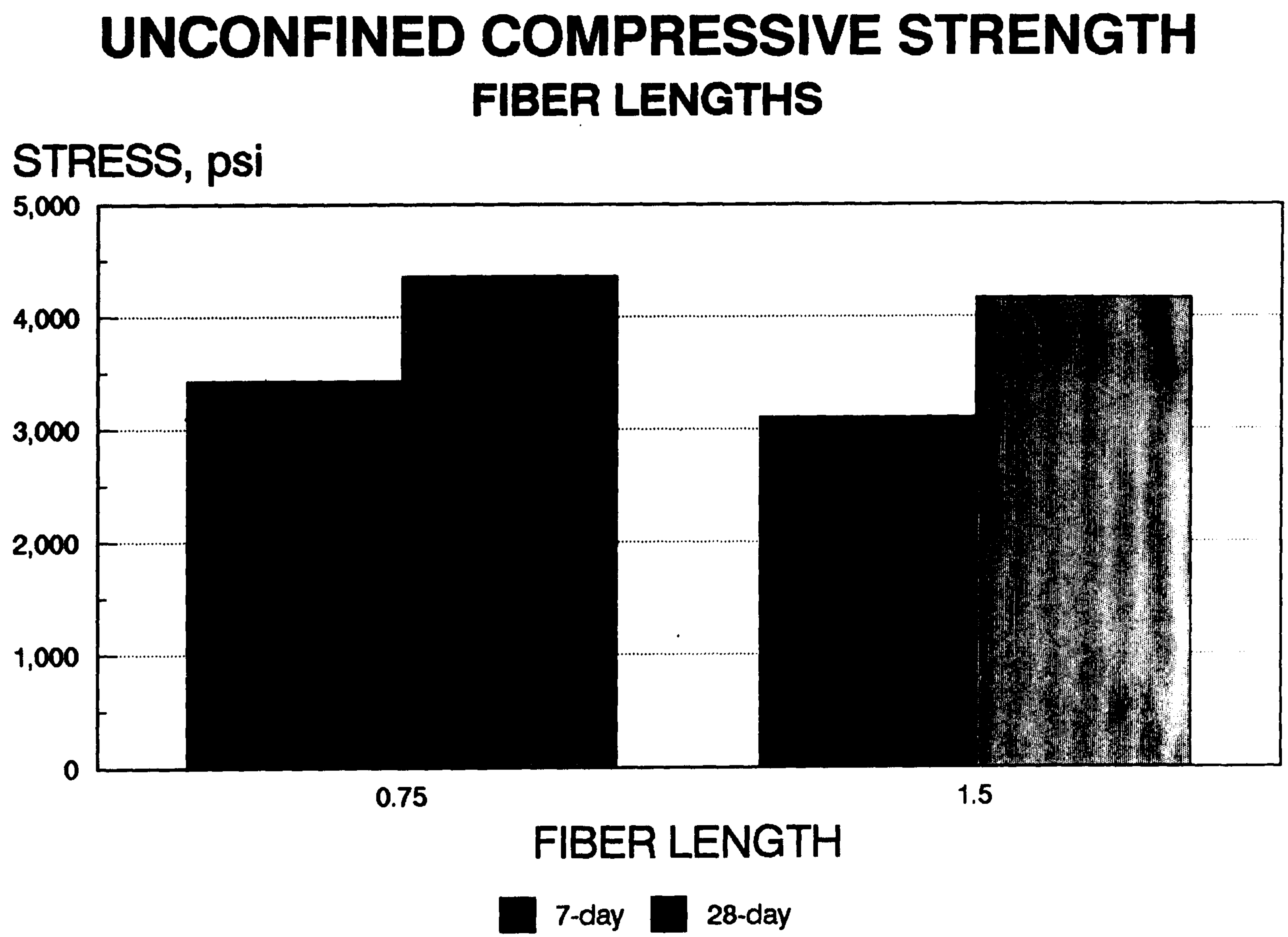
FIRST CRACK STRENGTH

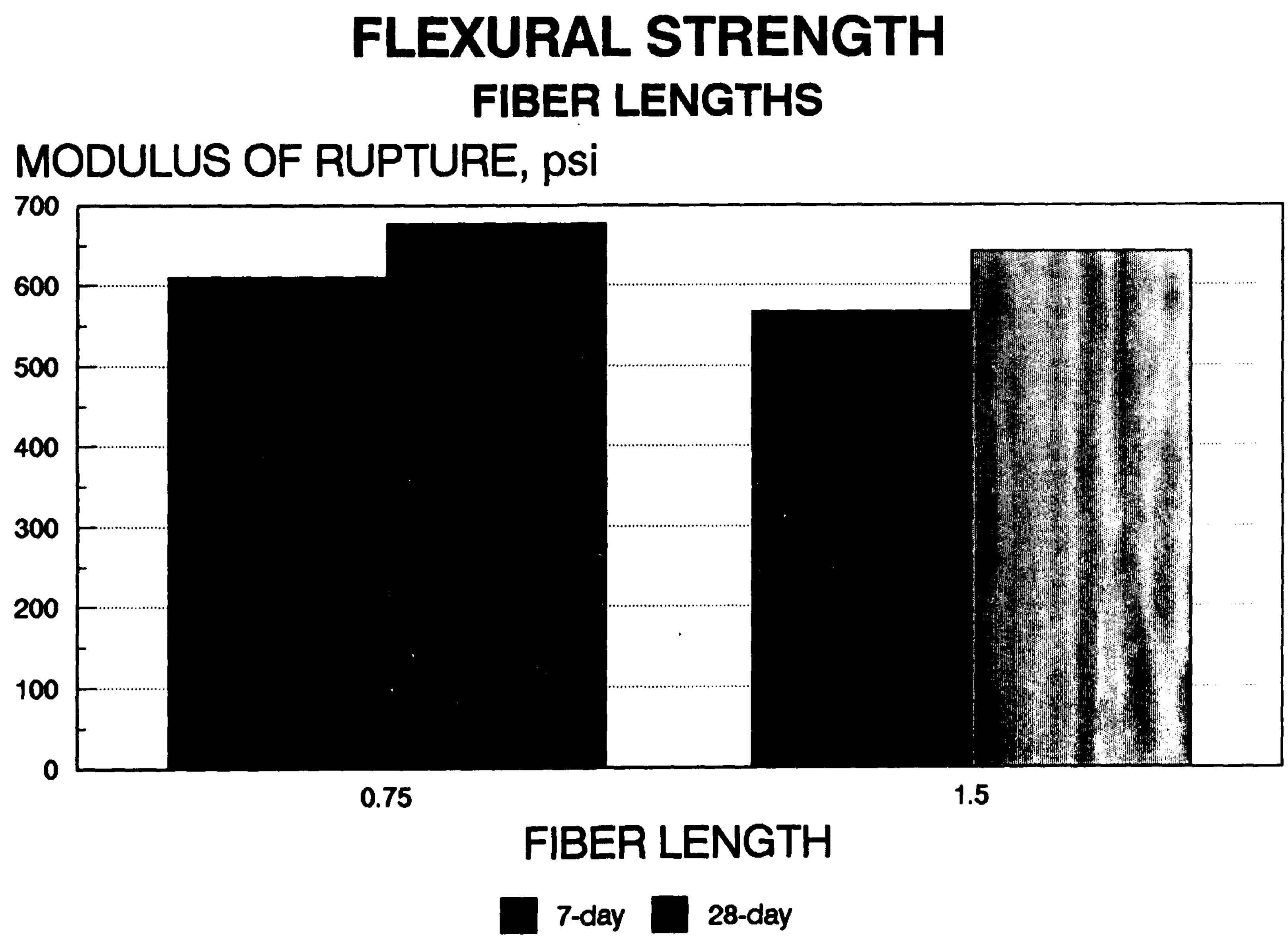
FIBER LENGTHS



TOUGHNESS
FIBER LENGTHS

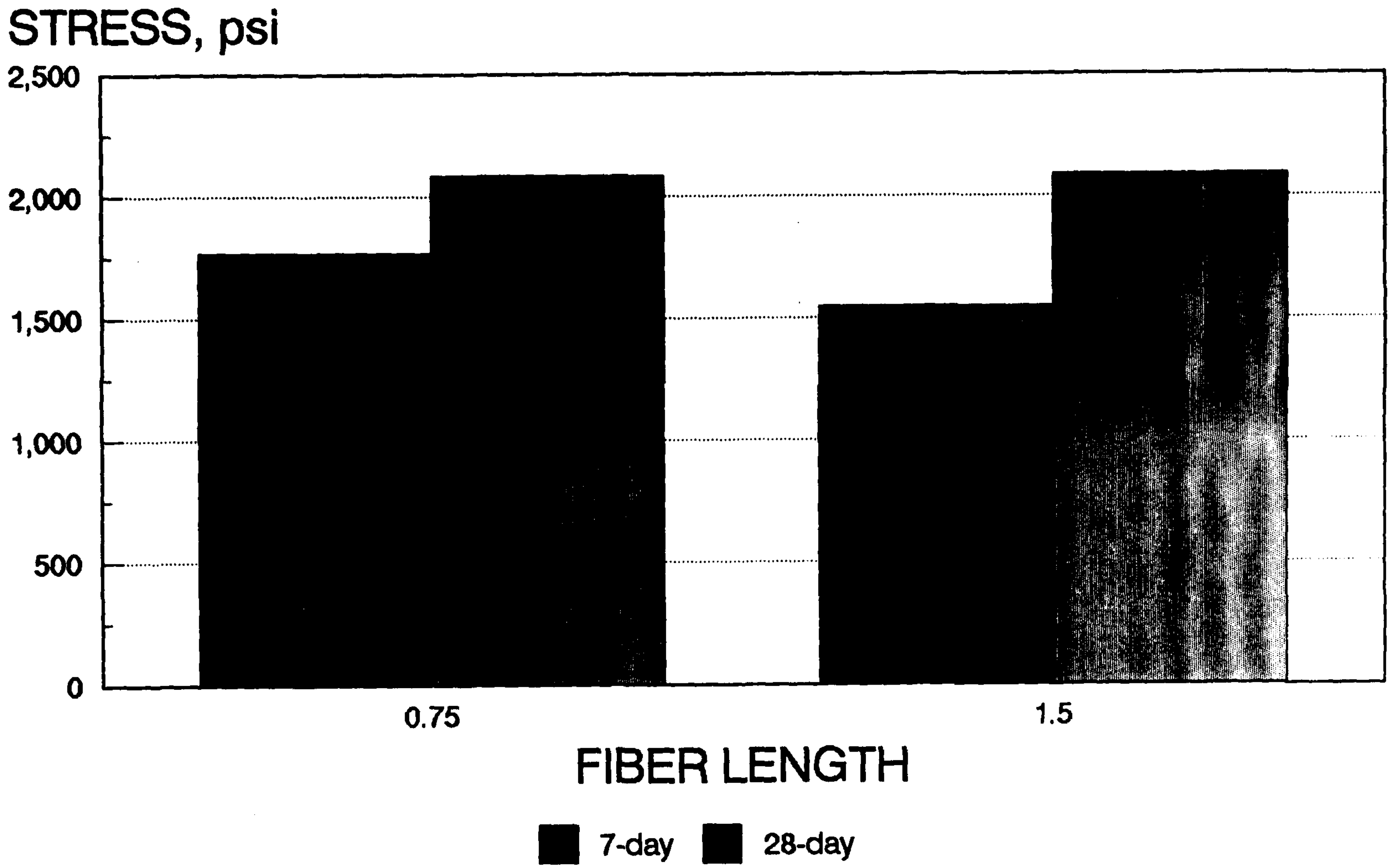



UNCONFINED COMPRESSIVE STRENGTH
FIBER LENGTHS
STRESS, psi
5,000
4,000
3,000
2,000
1,000
0
0.75
1.5
FIBER LENGTH
7-day
28-day

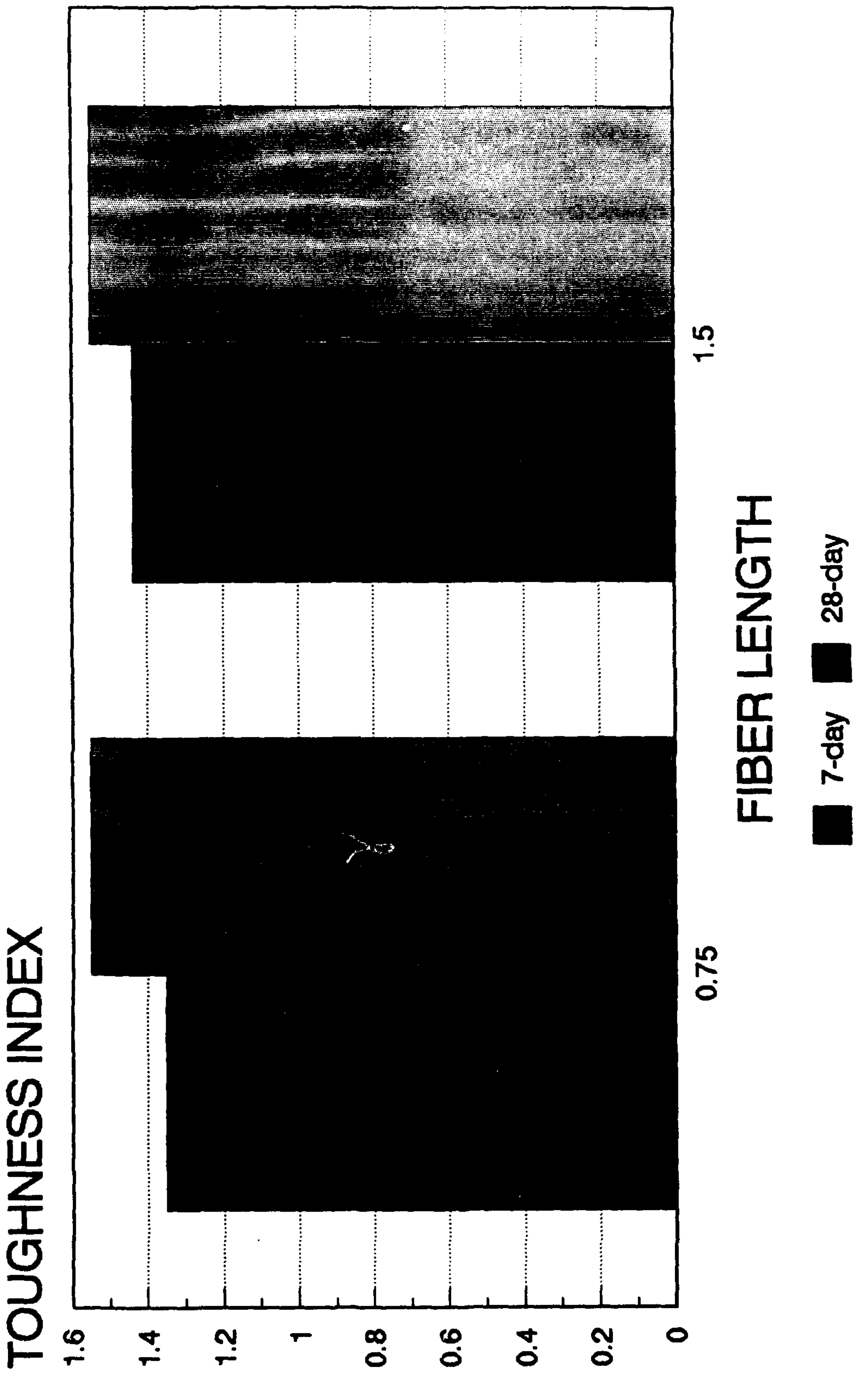


FLEXURAL STRENGTH
FIBER LENGTHS
MODULUS OF RUPTURE, psi
700
600
500
400
300
200
100
0
0.75
1.5
FIBER LENGTH
7-day
28-day

BOND STRENGTH
FIBER LENGTHS



I-5 TOUGHNESS INDEX
FIBER LENGTHS



I-10 TOUGHNESS INDEX

FIBER LENGTHS